PB-222 015

PYROLYSIS OF SOLID MUNICIPAL WASTES

SAN DIEGO CITY UTILITIES DEPARTMENT

PREPARED FOR
NATIONAL ENVIRONMENTAL RESEARCH CENTER

JULY 1973

Distributed By:

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National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

EPA-670/2-73-039
July 1973

PB 222 015

PYROLYSIS OF SOLID MUNICIPAL WASTES

By

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City of San Diego, California

Grant No. EP-00266
Program Element No. 1D2314

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Springfield VA 22151

Prepared for
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

BIBLIOGRAPHIC DATA SHEET	1. Report No. EPA-670/2-73-039	2.	3. Recipient's Accession No. PB-222 015
4. Title and Subtitle PYROLYSIS OF SOLID MUNICIPAL WASTES			5. Report Date 1973-issuing date 6.
7. Author(s) Donald A. Hoffman			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Utilities Department City of San Diego, California			10. Project/Task/Work Unit No. 11. Contract/Grant No. EP-00266
12. Sponsoring Organization Name and Address U.S. Environmental Protection Agency National Environmental Research Center Office of Research & Development Cincinnati, Ohio 45268			13. Type of Report & Period Covered Final 14.

15. Supplementary Notes

16. Abstracts

The objective of the project was to investigate the products of the pyrolysis of solid municipal wastes; the optimum temperature at which the process should be carried out; the volume reduction of wastes when pyrolyzed, and the potential of any byproducts produced. Although the wastes used in the experimentation were "typical San Diego refuse", the attempt was made to express the results in terms of such units that, hopefully, these data would be useful to other communities by adjustment in accordance with their own individual solid wastes classification. Experimental results were favorable in that waste volumes are significantly reduced and the process can be sustained by the incineration of its product(s) if the pyrolyzing equipment used has an overall thermal efficiency of 60 percent or over.

17. Key Words and Document Analysis. 17a. Descriptors

Refuse disposal, Wastes, *Waste disposal,*Pyrolysis, Stabilization, Temperature, Exposure, Refuse, Decomposition, Gases, Volatility, Retorts, Byproducts, Glass, Iron, Steels, Condensing

COLOR ILLUSTRATIONS REPRODUCED IN BLACK AND WHITE

17b. Identifiers/Open-Ended Terms

*Solid municipal wastes, *Solid waste disposal, Resource recovery, *San Diego, Solid residue, Waste reduction

17c. COSATI Field/Group 13-B

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Release to public	UNCLASSIFIED	79
	20. Security Class (This Page) UNCLASSIFIED	22. Price $4.85 $0.95

FORM NTIS-35 (REV. 3-72)
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FOREWORD

Man and his environment must be protected from the adverse effects of pesticides, radiation, noise and other forms of pollution, and the unwise management of solid waste. Efforts to protect the environment require a focus that recognizes the interplay between the components of our physical environment--air, water, and land. The National Environmental Research Centers provide this multidisciplinary focus through programs engaged in

- studies on the effects of environmental contaminants on man and the biosphere, and
- a search for ways to prevent contamination and to recycle valuable resources.

In an attempt to study the problem of solid waste disposal, this research project investigated the feasibility of pyrolysis as a method of processing solid municipal wastes and conserving sanitary landfill space.

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ABSTRACT

PROJECT

Research and Investigation.

TITLE

Pyrolysis of Solid Municipal Wastes

OBJECTIVES

To investigate the feasibility of pyrolysis as a method of stabilizing and decreasing the volume of solid municipal wastes and to determine the optimum temperature and period of exposure for various types and mixtures of refuse. To determine the composition of the hot volatile compounds resulting from the pyrolytic decomposition of refuse, investigate the gaseous products which could be used to provide heat for the system and what, if any, by-products can be recovered from the liquid tar-like material derived from the process. To investigate the properties of the solid residue to determine if it should be discarded as fill material or utilized as a fuel.

PROCEDURES

Samples of a "typical San Diego refuse", whose composition was determined by a landfill classification study, were pyrolyzed in air-tight retorts of two sizes - 4 inch diameter x 12 inch length and 18 inch diameter x 48 inch length. The retorts were charged with samples of 5, 10, 15, and 20 lbs./cu. ft. bulk density. Samples in the 4 inch diameter retort were pyrolyzed at 900°F, 1200°F, 1500°F, and 1700°F. Samples in the 18 inch

diameter retort were pyrolyzed at 1200°F and 1500°F. By the use of appropriate condensing systems the condensable portion of the hot volatile products of pyrolytic decomposition were collected, weighed, and analyzed. The non-condensable portion was passed through suitable measuring devices and, depending upon the quantity of gas evolved, either captures in a gas collection apparatus or flared as evolved.

FINDINGS

1) Pyrolysis is feasible as a method for the processing of solid municipal wastes in that the organic fraction of such wastes undergo a significant reduction in volume during the process; however, there still remains the development of reliable systems for the proper materials preparation and its handling into and out of the pyrolysis retort.

2) The energy content of the products of pyrolysis - the char and the hot vapor (noncondensable gases, tars, and liquid organics) is more than sufficient to sustain the process once it has been raised to the selected temperature. In equipment having the proper over-all thermal efficiency, the process may be sustained by the combustion of the hot vapor only.

3) The sulfur content found in the tars of the "crude vapor" indicate that the combustion of this hot vapor to sustain the process would give stack emissions well within Rule 53(a) of the San Diego County Air Pollution Control District governing such emissions (0.2% by volume as SO_2).

4) Use of pyrolysis by any community whose solid waste classi-

fication approximates that of San Diego (i.e. by volume, 26% noncombustibles and 74% combustibles) would result in a significant reduction in the sanitary landfill space used annually. This potential annual reduction could reach as high as 70% depending upon the character of the community's noncombustibles and the disposition of the char.

5) The optimum temperature of pyrolysis with the minimum pyrolyzing time occurs at 1500°F with material having a bulk density of around 15-20 lbs/cu. ft. in both a 4 inch diameter and 18 inch diameter retort.

6) The liquid fraction from pyrolysis is sufficiently complex to warrant a detailed and extensive investigation. Although the estimated retail market dollar value of the liquid organic compounds in this fraction is impressive, it may well be that the cost of processing and separation of this fraction to prepare the organic compounds for marketing would be so great as to render them non-competitive.

7) The carbonaceous residue resulting from the pyrolysis of municipal waste combustibles represents a rich and reasonably easily transportable source of energy. The Btu content of the carbonaceous residue from the pyrolysis of one ton of "typical San Diego combustibles" is equivalent to that of 1 barrel (42 gals.) of Bunker "C" fuel oil, i.e. about 5 million to 6 million Btu per ton.

8) The carbonaceous residue from pyrolysis, when properly handled and activated, provides a material whose adsorptive potential is equal or superior to some activated carbons now marketed commercially.

9) Most plastic materials when pyrolyzed at 1500°F depolymerize into carbon (plus inert fillers) and gas, and thus present no operating problem.

10) Glass softens during pyrolysis at 1500°F but not to the extent that it becomes fluid. Thus glass should not present an operating problem.

11) Iron and steel are unaffected by pyrolysis except that the solders used in fabrication of some cans will melt and run. The quantity of metals so effected is so small as to not cause operating problems. Aluminum cans at 1500°F behave much the same as glass.

12) Processing of solid municipal wastes by pyrolysis is a new and unique approach to this problem; but no capital costs or operating costs are available. It is estimated, however, that the overall unit cost of waste processing by pyrolysis would not exceed that experienced when using incineration and might possibly be lower. Until such a time as an adequately sized pyrolysis unit is constructed and operated, the economic feasibility of this process, when applied to solid municipal wastes, will remain a matter of conjecture.

I. BACKGROUND

Pyrolysis of wood is an ancient art. It was practiced by the prebiblical Egyptians not only for the recovery of charcoal, but also for the production of fluid wood tar and pyroligneous acid, which was useful for embalming.

For many decades, and perhaps centuries, the destructive distillation of wood (heating in the absence of oxygen) was the major source of charcoal, acetic acid, methyl alcohol, and acetone. During and following World War I, however, chemists learned how to produce acetone by fermentation, to synthesize acetic acid from calcium carbide, and to generate acetone from propylene. Coke, produced by the destructive distillation of coal, frequently replaced charcoal as a clean-burning source of carbon. After a brief flurry of activity during and shortly after World War II, the pyrolysis of wood became almost a forgotten art. Now it is being revived somewhat by the demand for high-grade activated charcoal (for cigarettes and for filtration or neutral grain spirits) and for tertiary sewage treatment processes. It is also being considered for advanced concepts of municipal solid waste processing.

Traditionally, the pyrolysis of wood has been carried out in batch operations, initially in earthen or brick-lined kilns and later in steel retorts, such that the source of heat from combustion is kept separate from the wood being pyrolyzed. Batch operations involve certain inherent thermal inefficiencies in the preheating and post-cooling processes. Furthermore, kilns and retorts are necessarily restricted in size so that they cannot process much wood at a time.

The relative yields of charcoal, gases, and chemical products depend on the nature of the wood, the size of logs or wood chips, the density of packing, the degree of preheating and predrying, the ultimate temperature of pyrolysis, and the rate at which it is achieved. For example, if heating is carried out rapidly in small retorts and at a high temperature, the yield of combustible gas is high but the production of charcoal, acetic acid, and tar is low. On the other hand, if heating is slow and large retorts are used, the production of combustible gas is minimized while the yield of charcoal, acetic acid, and pyroligneous aqueous products is maximized. Hence, the optimum operation of the system depends on the products most wanted.

The percentage by weight of products from pyrolysis of various types of wood have been reported as follows:

Product	Hard-wood (1)	Various Woods: Slowly Heated (2)	Various Woods: Quickly Heated (2)	Various Woods (3)
Charcoal	25.2%	26.7-34.7%	21.9-27.7%	24.4-26.6%
Tar and oil	5.0	3.7- 5.9	3.2- 9.8	8.6-11.9
Methanol, acetic acid, etc.	4.8	2.7- 5.6	2.4- 4.4	4.2- 8.9
Water and pyroligneous acid	46.7	41.0-45.8	39.5-42.0	24.3-44.9
Gas	18.3	17.2-24.4	24.1-35.6	16.5-21.0

Among the various types of wood, in general, the pyrolysis of fir yields the highest percentage of gas, but the least water and pyroligneous acid; while oak, slowly heated, gives the

highest recovery of charcoal. The gas evolved is about 50-55 percent carbon dioxide, 20-30 percent carbon monixide, and about 15 percent methane; but these percentages could be changed by more careful exclusion of air.

Batch pyrolysis of wood in the U.S. has generally been achieved by loading the wood on steel buggies on standard-gage railroad track in batches of 6 to 10 cords; running the buggies into steel retorts hung in firebrick settings and heated by coal or natural gas; with cycles of about 24 hours for heating, pyrolysis, and cooling. Continuous pyrolysis of wood has been undertaken in Finland by means of an insulated masonry tunnel about 220 ft. long (divided into several compartments for preheating, pyrolysis, and cooling) through which railroad cars loaded with wood are drawn slowly. Heat is supplied through iron tubes within the tunnels such that no gases from combustion enter the chamber or come in contact with the wood. Every hour a railroad car enters the tunnel and one emerges at the other end. The total time in the tunnel (preheating, pyrolysis, and cooling) is about 15 hours.

Pyrolysis is also used for the production of high-grade charcoal from finely ground coconut shells and other selected carbonaceous material. For this purpose a continuously fed rotary kiln with an external heat source is employed. Care must be taken to minimize the access of air to the pyrolysis chamber and to cool the hot charcoal adequately on emerging before it comes in contact with the ambient air. The gaseous products of pyrolysis can be used as a source of external heat for the rotary kiln.

Rotary kilns similar to that described above have also been used for pyrolysis of carbonaceous industrial refuse such as wood chips, sawdust, cardboard, and packing materials. The rotary kilns can operate successfully provided that the material fed to them is sufficiently small in size and readily conveyed to and from the kiln. The major difficulties in this operation appear to arise from material-handling problems.

It would seem, therefore, that any optimum pyrolysis system for material as heterogeneous or diverse as municipal refuse should include a reliable fool-proof method for getting the assorted trash into and out of the pyrolysis chamber. For this reason, the extensive historical experience with destructive distillation of wood should provide clues for effective pyrolysis of mixed municipal refuse.

II. Experimental:

The City of San Diego owns and operates three sanitary landfill areas designated as Chollas, in the southeastern part of the City; Miramar landfill on the north side and Arizona landfill in the central section of the City. These three sites are under the jurisdiction of the Public Works Department. It is estimated that the Chollas fill will be closed in 1972 and the other two, Arizona and Miramar, in 1975.

It is the responsibility of the householder to place his refuse cans at the points of collection and to remove them after collection. Collection points are at the curbs or, in a few locations, in an alley. It is a "combined collection", i.e., garbage is not segregated. Collections are made once weekly in residential areas. In business areas as many as

six collections per week are made, depending upon the amount of refuse to be collected.

Of the three City-owned and operated fill sites, the public has access to two (Chollas and Miramar) while the third (Arizona), is reserved exclusively for city-collected refuse.

To establish a standard composition for the material to be experimentally pyrolyzed, a classification study was made of the material drawn into the two fill sites (Chollas and Miramar) open to the public. The study actually covered a total of 40 days - 10 days at each of the two fill sites during the months of August and September and 10 days at the same sites during the month of March. Staggering the survey periods in this manner covered solid wastes drawn into the fill sites in both the dry and the wet periods. During the survey every vehicle, both privately and city owned, that brought any material into these fill areas was counted and the volume and type of material recorded. By actual count 18,317 vehicles were inspected and their volumes recorded. An estimated total of 30,000 tons of solid wastes were inspected during the survey. Additionally many packer loads picked up door to door by the City Sanitation crews were dumped in agreed upon areas at the fill sites and hand sorted, weighed and classified.

Material as received at the fill areas and which is typical of the residential pickup by the city owned packers is shown in Table I.

All retort charges pyrolyzed were of the composition given in Table I, "% On Dry Basis, without Metal & Glass" so that results might be expressed on the basis of "per pound

Table I

Typical San Diego Residential Pickup

Constituent	% By Weight As Received	% By Weight Moisture	% By Weight, Dry Basis with Metal & Glass	% By Weight, Dry Basis without Metal & Glass
Paper	46.16	8.23	42.36	50.40
Yard trimmings	21.14	51.30	10.30	12.25
Wood	7.48	10.50	6.69	7.96
Rags	3.46	7.40	3.20	3.82
Rubber	4.73	9.74	4.27	5.08
Plastics	0.27	0.06	0.27	0.32
Garbage	0.81	57.80	0.34	0.40
Metal	7.64	0	7.64	0
Glass	8.31	0	8.31	0
Moisture	- -	- -	16.62	19.77
TOTAL	100.00		100.00	100.00

of typical San Diego combustibles". The relative proportions of combustibles and noncombustibles will vary from community to community and reporting on the basis of "per pound of typical San Diego combustibles" would provide information which any interested community might adjust in accordance with its own combustible/noncombustibles ratio.

Although this basis of reporting would be helpful, even better would be a thorough detailed investigation of the results obtained by the pyrolysis of each individual component, i.e. paper, yard trimmings, garbage, etc. It would seem that possession of such information would, in the case of a community, make the applicability or inapplicability of pyrolysis a matter of calculation from its own solid waste classification study.

In the case of San Diego, the fill survey showed that the concrete rubble, fill dirt and construction debris hauled to the landfill sites by contractors constituted more than 50% by weight of the total material brought in. Adjusting the gross total of solid wastes covered by the survey for combustibles and noncombustible, the survey results are:

		% By Volume	% By Weight
1)	Combustibles (Organics amenable to Pyrolysis)	73.93%	42.69%
2)	Non-combustibles (Inorganics, metals, glass, etc., not amenable to Pyrolysis)	26.07%	57.31%
		100.00%	100.00%

The city's fill regulations require that the construction debris and fill dirt hauled to the fill by the contractors must be placed in specified areas. This material is used for cover during operation.

Using material of the constitution given in Table I, "% on Dry Basis without Metal & Glass", pyrolysis work was carried out in two sizes of equipment. Initial work was done in a stainless steel retort having a diameter of approximately four inches and a length of approximately twelve inches. The computed volume of this retort was 0.0845 cu. ft. Pyrolysis was performed in this small retort at four temperatures: 900°F., 1220°F., 1500°F. and 1700°F. Material bulk densities of the charges pyrolyzed were nominally 5, 10, 15, and 20 pounds per cubic foot except that only one bulk density of charge (5 pounds per cubic foot) was investigated at 1700°F. Further work at 1700°F. was abandoned when it was observed that results obtained at 1700°F and 5 pounds per cubic foot bulk density were not as favorable as those resulting from pyrolysis at 1500°F and 5 pounds per cubic foot bulk density.

At 1500°F., five samples with a material bulk density of 25 pounds per cubic foot were pyrolyzed. Attempts were made to prepare samples with 30 pounds per cubic foot bulk density. It was found that at this density the "typical San Diego refuse" would "weep", i.e., moisture flowed from the material. Because the loss in moisture constituted a change in composition of the sample, no samples having a bulk density greater than 25 lbs. per cubic foot were pyrolyzed.

Figure I is a schematic drawing of the apparatus used in conjunction with the small 4" diameter retort. The retort is loaded with typical waste combustibles, the face flange bolted on, and the outlet tube downstream of the tar trap connected to the condensing system. The charged retort and the entire system are purged with helium gas in the amount

PYROLYSIS BATCH SCHEMATIC

4 INCH DIAMETER RETORT

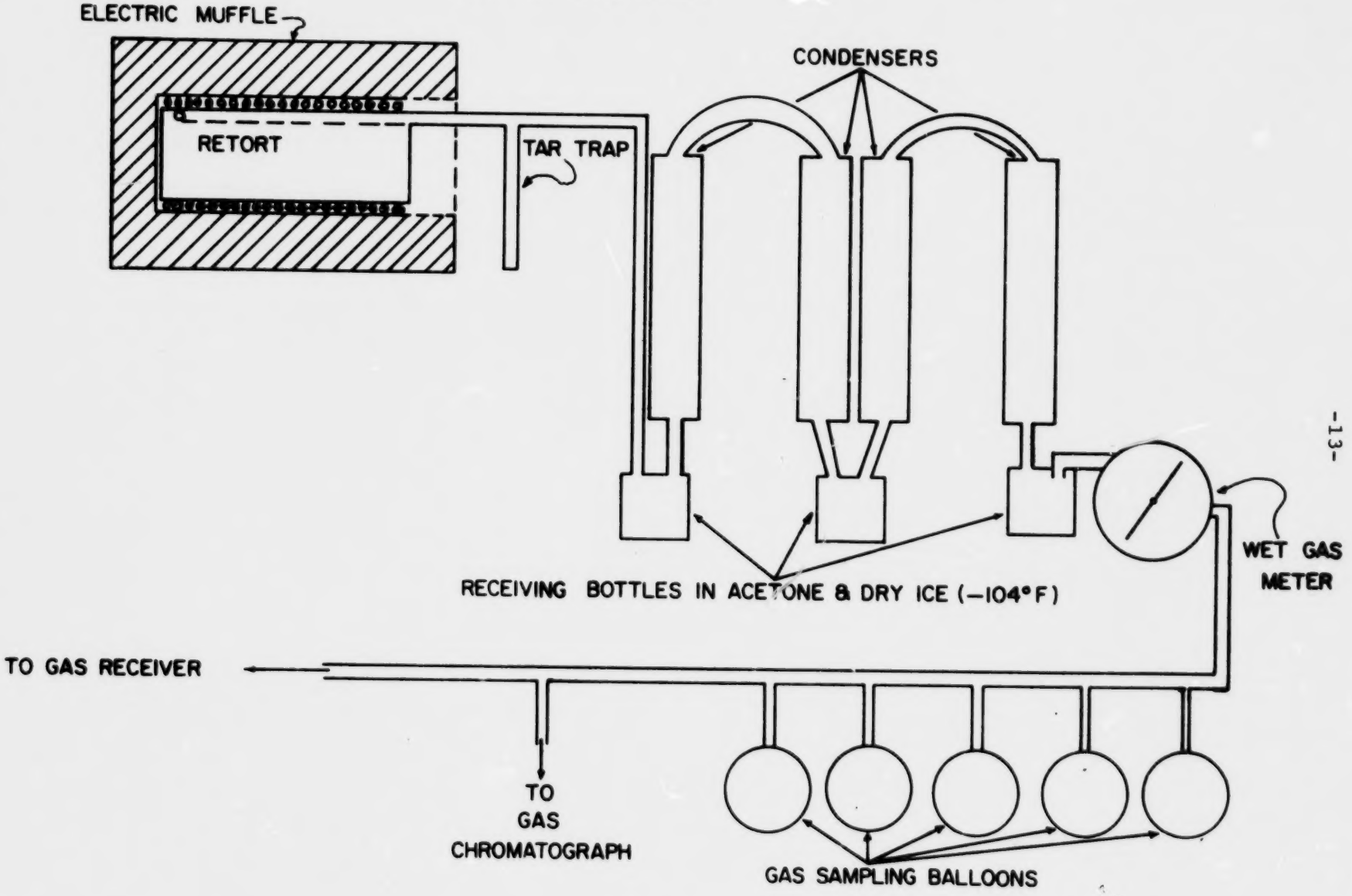

FIGURE 1

of about eight times the volume of the system. This initial purge gas is run to waste.

After purging, the loaded retort is placed in the electric muffle which has been raised to and maintained at the predetermined pyrolyzing temperature. As pyrolysis takes place, the distillate leaves the retort through the perforated outlet line, the tars and heavier fractions condense immediately outside the furnace in the tar trap, the lighter fractions are collected in the receiving bottles submerged in acetone and dry ice, and the non-condensable gases pass on through the gas meter and a gas-sampling manifold to a gas receiving balloon. Upon completion of a run the apparatus is again purged with helium to sweep out any evolved gases remaining in the system. This purge gas is measured and delivered into a large weather balloon which is the main receiver of the evolved gases. After completion of the helium post purge, the apparatus is disassembled, the char removed from the retort and weighed and the tars and pyroligneous acids washed from the tar trap and condensing system with a known weight of solvent and determined gravimetrically. During the run, several gas samples are taken in smaller balloons downstream of the gas meter. The analyses of the gases in the small ballons reflect the change of composition of the evolved gases during a run.

Gas chromatographic analyses of the contents of all gas-sampling ballons are completed within 4 hours of the end of a run. All gas sampling ballons are checked for helium diffusion; diffusion is less than 1% in 24 hours.

To compare the time of the experimental pyrolysis runs it was essential that a definition of "pyrolyzing time" be

developed. This was done from a study of cummulative gas volume and the instantaneous rate of gas evolution as functions of the time of heating. The definition agreed upon was that "pyrolyzing time is the time required to produce the 85% of gas volume lying between the first 10% and the last 5% of the total gas volume evolved from a retort batch".

This criterion was applied to each individual pyrolyzing heat performed during the project.

In the follow-on work with the 18 inch diameter by 48 inch length retort, investigations were concentrated on the 1200°F and 1500°F temperatures using retort charges of 5, 10, 15 and 20 pounds per cubic foot bulk densities. Work with the 4 inch diameter retort had already shown that results at 900°F and at 1700°F were not satisfactory.

The total weight of refuse charged into the 4 inch diameter retort varied from about .37 pounds at 5 pounds per cubic foot bulk density to about 1.7 pounds at 20 pounds per cubic foot bulk density and made it possible to manhandle a loaded retort quite easily. With the 18 inch diameter retort, however, refuse charges of comparable bulk densities varied from 35 pounds to 141 pounds. Because of the great increase in retort charge weights, it was necessary to handle the loaded retorts with a chainfall. The retort and condensing system were not purged with helium gas as had been the apparatus used in conjunction with the 4 inch diameter retort.

When making a run with the 18 inch diameter retort, the retort was filled with the proper weight of "typical San Diego refuse", the top bolted down securely and the loaded retort

hoisted up and then lowered into the furnace. During the loading of the retort, the furnace was raised to 900°F. The temperature of 900°F was found to be the maximum furnace temperature which permitted a person to bolt down the top of the furnace after the loaded retort had been lowered into place. The discharge lines from the retort to the condensing system were hooked up and the furnace with its charge allowed to come to the selected 1200°F or 1500°F pyrolyzing temperature as set by the automatic temperature controller on the furnace.

The gas sampling and the condensing system used in conjunction with the 18 inch diameter retort were essentially the same as the systems used with the 4 inch diameter retort although much larger. Figure 7 shows this equipment.

The much greater volume of gas evolved (900 + cubic feet at 1500°F/20 lbs. pcf bulk density) made it necessary to alter the gas sampling and storage routine previously employed. Gas sampling was done by measuring into a weather balloon, 0.10 cubic feet for every 10 cubic feet of gas evolved by pyrolysis. This gave a composite gas sample over the entire pyrolyzing cycle. No equipment of sufficient capacity to hold the entire volume of gas evolved was available so after passing through a water scrubber, the evolved gases were flared as generated.

III. RESULTS

At room temperature, the products resulting from the pyrolytic decomposition of the organic fraction of solid municipal wastes exist as noncondensable gases, liquids and a solid residue of carbonaceous material or char. Material balances were computed after every heat by dividing the sum of the weights of the noncondensable gases, liquids and solid residue by the

Figure 2

Condensing System on left, Pit Furnace used as heat source on right, Gas Meter in background

weight of the refuse sample charged into the retort before pyrolyzing. In the main, material accountability was good. The arithmetic mean of the material balances from all work with the 4 inch diameter retort was 99.44% and that from the 18 inch retort was 99.36%. Table 2 shows the material balances from the 4 inch diameter retort work and Table 3 shows those from the 18 inch diameter retort.

Gases

Analysis of a sample of the evolved pyrolytic gases taken directly from the gas stream shows these gases to be hydrogen, carbon dioxide, carbon monoxide, methane, ethane, and ethylene. No traces of nitrogen or oxygen were found in the evolved gases when sampling direct from the gas stream into the gas chromatograph as was done during work with the 4 inch diameter retort; therefore, oxygen and nitrogen probably are not constituents of the evolved noncondensable gases. Occasionally, traces of both these gases have been detected in the contents of the gas-sampling ballons, but this is attributed to the inability to completely evacuate the ballons prior to sampling.

Gas analyses from the 4 inch diameter retort are given in Table 4. Table 5 shows the gas analyses when pyrolyzing "Typical San Diego Combustibles" in the 18 inch diameter retort.

The individual gas constituents vary with changing pyrolyzing conditions, A change of pyrolyzing temperature appearing to bring about more noticeable change than does a change in the bulk density of the material pyrolyzed.

Analysis of the evolved gases was done on a gas chromatograph utilizing dual columns; one column being molecular sieve 5A and the other being Polypak-2. This analytical technique

Table 2

MATERIAL BALANCES OF MATERIAL PYROLYZED

Percent by Weight

4 inch Diameter Retort

Temp. °F	Nominal Material Bulk Density - lbs/cu.ft.				
900	5	10	15	20	25
Gases	12.33	12.22	12.18	12.54	
Condensables	61.08	60.76	60.07	58.67	
Char	24.71	26.78	27.01	27.37	____
Material Accounted for	98.12	99.76	99.26	98.58	*
1200					
Gases	18.64	19.46	19.09	19.75	
Condensables	59.18	57.87	58.92	55.22	
Char	21.80	20.96	21.15	24.26	____
Material Accounted for	99.62	98.29	99.16	99.23	*
1500					
Gases	23.69	27.62	27.94	25.89	28.05
Condensables	59.67	50.74	51.51	52.37	51.67
Char	17.24	21.00	20.40	21.48	20.19
Material Accounted for	100.60	99.36	99.85	99.74	99.91
1700					
Gases	24.36				
Condensables	58.70				
Char	17.67				
Material Accounted for	100.73	*	*	*	*

* Not Determined

Table 3

MATERIAL BALANCES OF MATERIAL PYROLYZED

Percent by Weight

18 inch Diameter Retort

Temp. °F	Nominal Material Bulk Density - lbs/cu.ft.			
1200	5	10	15	20
Gases	28.95	31.29	34.54	30.77
Condensables	47.57	43.31	40.39	38.95
Char	23.27	24.34	24.06	25.56
Material Accounted for	99.79	98.94	98.99	95.28
1500				
Gases	31.75	37.10	40.42	35.46
Condensables	43.39	42.05	39.90	36.46
Char	24.24	23.19	23.17	24.77
Material Accounted for	99.38	102.34	103.49	96.69

Table 4

Noncondensable Gases
(Percent by Volume)

4 Inch Diameter Retort

Tempertures °F	Material lbs. Per cu. ft.	CO_2	CO	CH_4	H_2	C_2H_6	C_2H_4
900	5	44.77	33.50	12.43	5.56	3.03	0.45
	10	45.14	34.51	12.21	5.22	1.90	1.01
	15	47.04	30.67	13.69	5.14	2.44	0.93
	20	47.41	32.42	11.71	5.65	1.86	0.94
1200	5	31.78	30.49	15.91	16.58	3.06	2.18
	10	26.41	30.51	19.16	19.97	1.93	2.02
	15	25.99	30.96	17.91	21.94	1.83	1.37
	20	27.24	28.71	18.80	21.32	2.23	1.58
1500	5	20.59	34.12	13.73	28.55	0.77	2.24
	10	21.58	27.19	15.46	32.10	1.13	2.55
	15	21.92	24.84	15.26	34.79	0.94	2.24
	20	21.28	25.10	17.48	32.64	1.04	2.45
	25	21.64	23.31	16.23	34.96	0.80	3.05
1700	5	18.31	35.25	10.45	32.48	1.07	2.43

Table 5

Noncondensable Gases
(Percent by Volume)

18 Inch Diameter Retort

Temperatures °F	Material lbs. Per cu. ft.	CO_2	CO	CH_4	H_2	C_2H_6	C_2H_4
1200	5	31.33	19.40	16.41	29.87	0.95	2.04
	10	30.42	20.02	17.85	28.92	0.85	1.93
	15	30.68	18.06	18.09	30.59	0.74	1.85
	20	27.19	16.36	17.87	36.20	0.80	1.58
1500	5	25.20	25.08	13.42	33.98	0.74	1.57
	10	25.50	25.46	14.28	32.81	0.47	1.47
	15	24.52	27.25	13.06	33.48	0.32	1.36
	20	22.27	24.89	11.39	40.30	0.20	0.96

was developed during the course of this project and is described in detail elsewhere (4).

Prior to starting work with "typical refuse" retort loads, an experimental run was made using a 4 inch diameter by 12 inch long wood dowl as the furnace charge. This run covered the range of 150°F to 1200°F. The temperature was raised in increments of 50°F with a 20 to 30 minute temperature stabilization following each 50°F temperature raise. The gases evolved were first detected chromatographically in the following order and at the noted furnace temperatures:

TABLE 6

Constituent	Furnace Temperature °F
Carbon Dioxide (CO_2)	500
Carbon Monoxide (CO)	600
Methane (CH_4)	750
Hydrogen (H_2)	1000

During the pyrolysis of a batch of typical San Diego refuse, the maximum rate of gas evolution occurs at, or slightly before, the retort shell reaches the pyrolysis temperature as shown in Figure 3 and Figure 4. Figure 3 is Run #174 at a temperature of 1500°F while Figure 4 is Run #178 at a temperature of 1200°F. Figure 5 depicts the change in volume percentage of the various gases evolved at 1200°F as a function of pyrolyzing time. Samples were taken of the evolved gases at 15 and 30 minute intervals during the entire duration of the pyrolyzing run. Both Run #174 and #178 were made in the larger 18 inch diameter retort.

PYROLYSIS

RUN NO. 174

TEMPERTURE 1500°F

MATERIAL BULK DENSITY 15 LB/FT^3

TYPICAL SAN DIEGO REFUSE

18 INCH DIAMETER RETORT

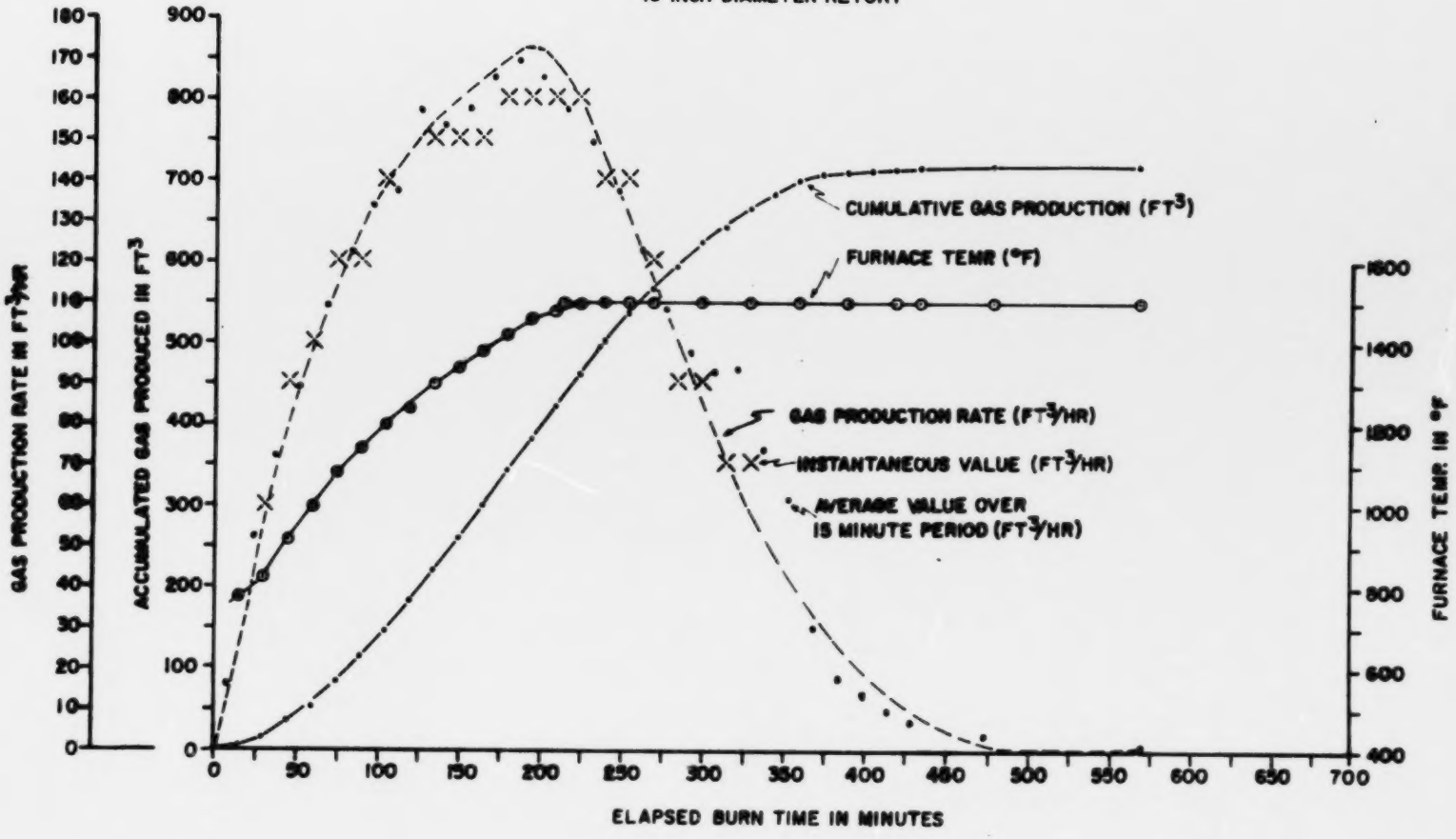
GAS PRODUCTION RATE IN FT³/HR
ACCUMULATED GAS PRODUCED IN FT³
FURNACE TEMP IN °F
ELAPSED BURN TIME IN MINUTES
CUMULATIVE GAS PRODUCTION (FT³)
FURNACE TEMP (°F)
GAS PRODUCTION RATE (FT³/HR)
INSTANTANEOUS VALUE (FT³/HR)
AVERAGE VALUE OVER 15 MINUTE PERIOD (FT³/HR)

FIGURE 3

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PYROLYSIS

RUN NO. 178

TEMPERATURE 1200°F

MATERIAL BULK DENSITY 15 LB/FT^3

TYPICAL SAN DIEGO REFUSE

18 INCH DIAMETER RETORT

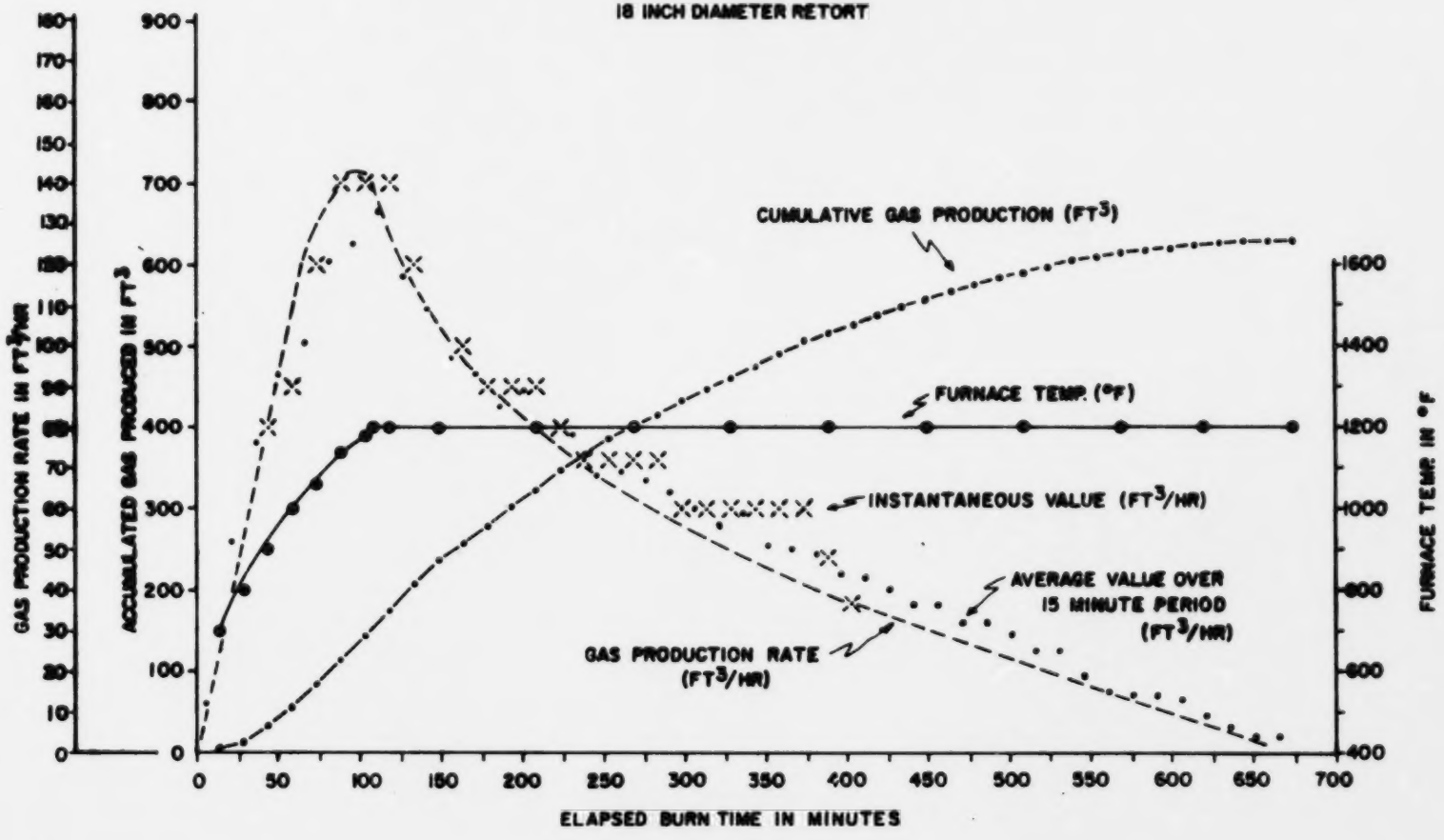

FIGURE 4

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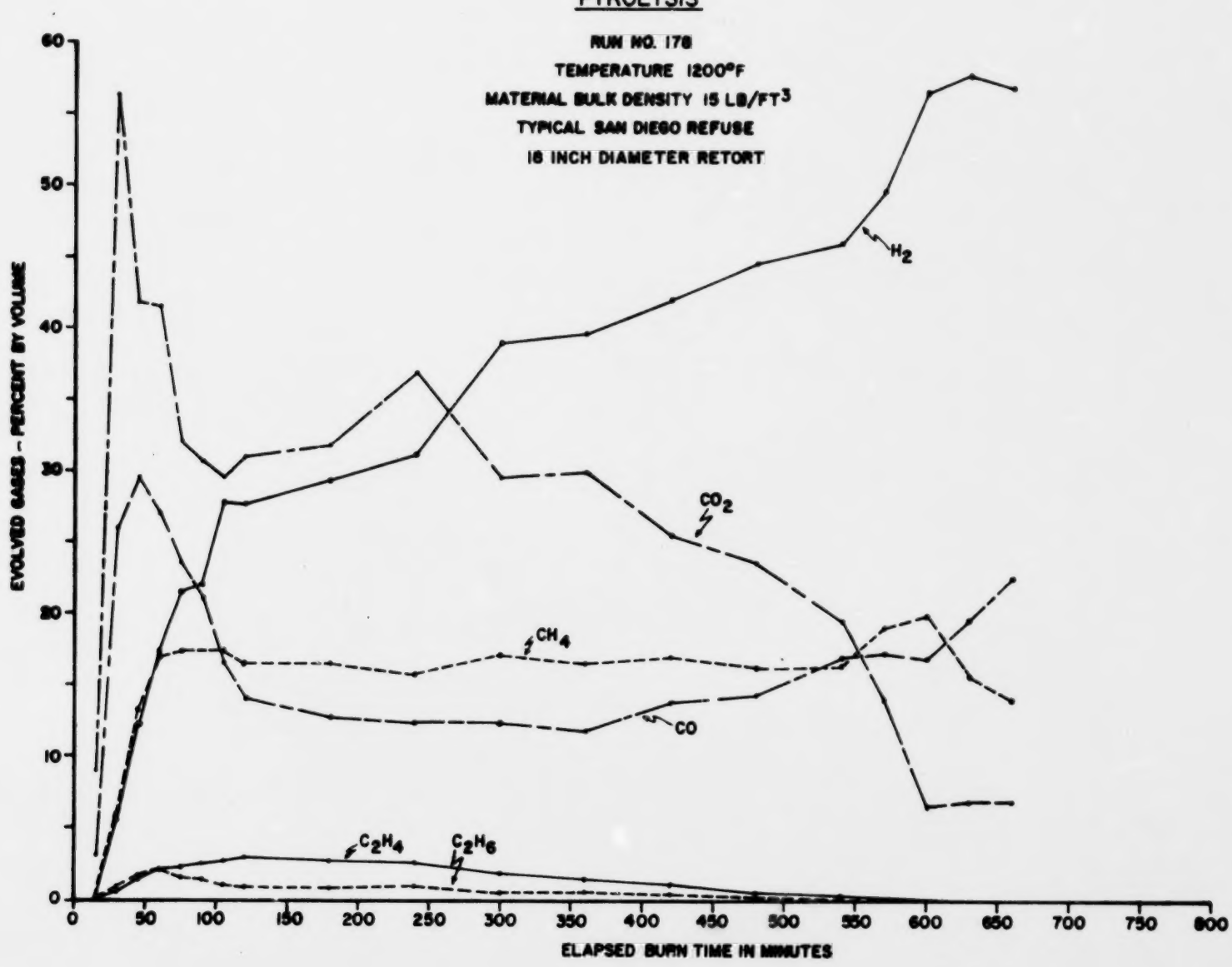
PYROLYSIS
RUN NO. 178
TEMPERATURE 1200°F
MATERIAL BULK DENSITY 15 LB/FT3
TYPICAL SAN DIEGO REFUSE
18 INCH DIAMETER RETORT
EVOLVED GASES - PERCENT BY VOLUME
ELAPSED BURN TIME IN MINUTES
H2
CO2
CH4
CO
C2H4
C2H6
0
10
20
30
40
50
60
0
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800

FIGURE 5

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Characteristically, curves drawn from comparable data collected from pyrolyzing in the 4 inch diameter retort followed the general configuration of Runs #174 and #178, i.e. maximum gas evolution occurring at, or just prior to, the retort shell reaching the selected pyrolyzing temperature and then decreasing with time of pyrolyzing. In every batch pyrolyzed, the first two evolved gases detected were carbon dioxide (CO_2) and carbon monoxide (CO).

To check out the gases evolved in a continuous (dynamic) versus a batch (static) pyrolyzing condition, a 4 inch diameter pyrolyzer was constructed. This equipment consisted of a 4 inch diameter horizontal feed pipe fitted with a piston which could be advanced by a variable speed motor drive to push typical refuse into a 4 inch diameter pyrolyzing zone 18 inches in length. After pyrolyzing, the char was pushed out of the pyrolyzing zone and dropped into an airtight char catcher.

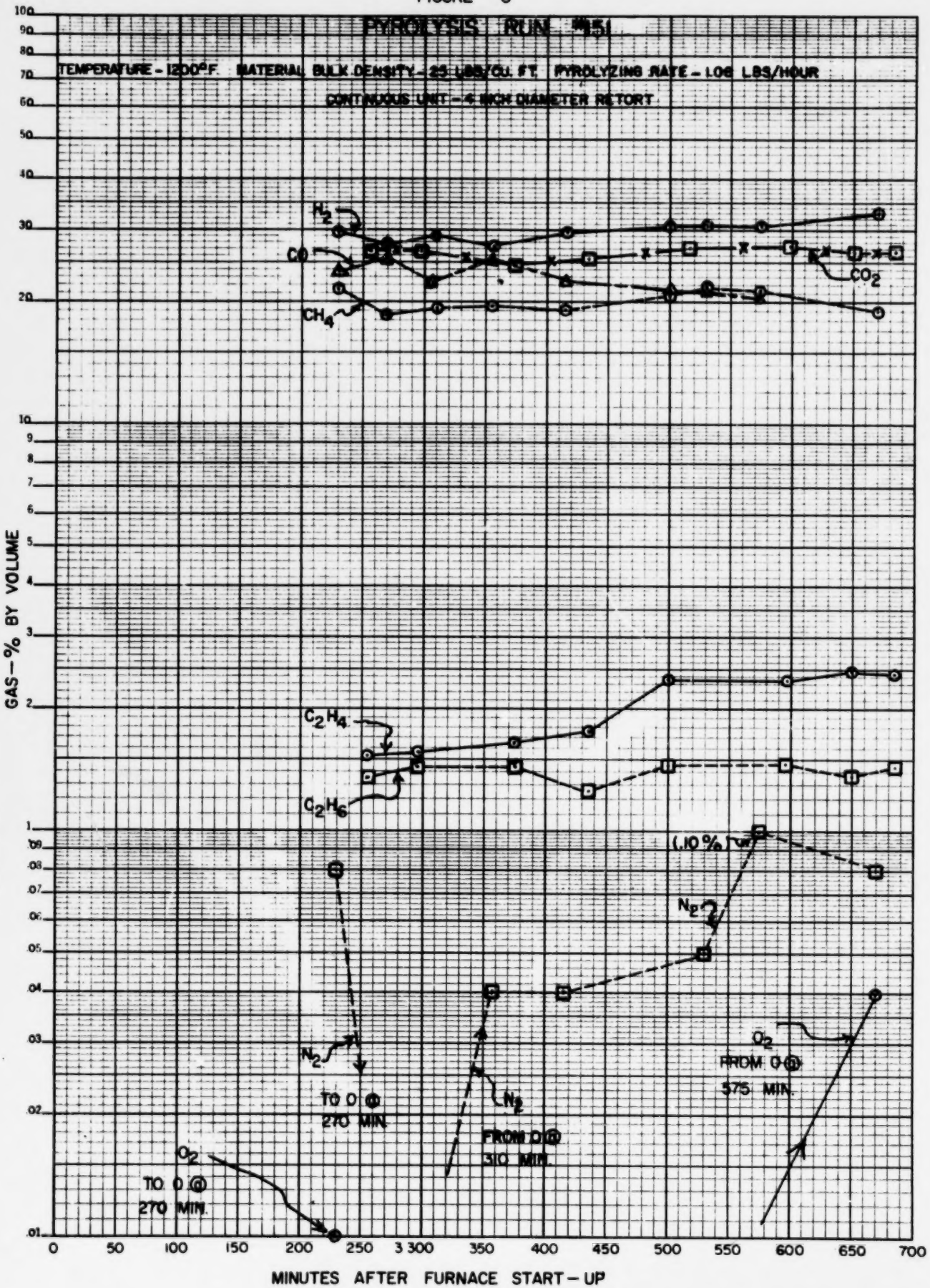
Operation of this equipment substantiated the contention that the composition of the evolved pyrolysis gases would eventually come to a relatively steady state. Figure 6 is a chart of the periodic gas analyses from Run #151. (The .10-1.00 cycle is omitted in Figure 6. No analytical results fell within these values).

Liquids

Of the gaseous, liquid and solid products of pyrolysis, the liquid product presented the greatest analytical difficulty.

This fraction, at room temperature, consists of water plus various organics which are formed and/or volatilized during pyrolysis. The liquids contain not only the original free moisture of the sample pyrolyzed, but also water formed by the

FIGURE 6


PYROLYSIS RUN #51
TEMPERATURE - 1200°F. MATERIAL BULK DENSITY - 25 LBS/CU. FT. PYROLYZING RATE - 106 LBS/HOUR
CONTINUOUS UNIT - 6 INCH DIAMETER RETORT
H2
CO
CO2
CH4
C2H4
C2H6
N2
O2
TO 0 @ 270 MIN.
FROM 0 @ 310 MIN.
FROM 0 @ 575 MIN.
(.10 %)
GAS — % BY VOLUME
MINUTES AFTER FURNACE START — UP
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
50
100
150
200
250
3 300
350
400
450
500
550
600
650
700

degradation of the organic material of the charge. Water content of this fraction after settling of the tars in some cases approximated 97% to 98% by weight. Attempts to separate the various organics by fractional distillation were unsuccessful. Presumably, the organics are azeotropic in form.

As collected during a pyrolysis run, the liquid product contained such a high percentage of water that it could not be ignited in a Parr bomb. In order to develop as much calorific information as possible, weighed portions of the liquids were dried at 103°C and the residue ignited in the Parr bomb. The quantity of this residue (tar) expressed as a percentage by weight, both of the liquid condensables and also of "typical San Diego refuse combustibles" is given in Table 7 for the 4 inch diameter retort. Table 8 shows comparable results obtained when using the 18 inch diameter retort.

It was fully realized that this procedure resulted in the loss of compounds which were volatile at temperatures up to 103°C but at the same time it did provide a method by which at least a partial calorific value of the liquids could be determined.

Later in the project, a contract was made with West Coast Technical Service Inc. for a much more sophisticated analysis of the liquids. Samples of the liquid product resulting from the pyrolysis of "typical San Diego refuse" with bulk densities of 5, 10, 15 and 20 pounds per cubic foot at 1200°F and 1500°F were analyzed by West Coast using gas chromatography, mass spectrometry and infrared spectrophotometry. Forty-nine (49) compounds were detected by chromatography. Of these, sixteen (16) (including water and carbon dioxide) appeared in

Table 7

Residue on Evaporation (103°C) of Condensables
(Percent by Weight)
4 Inch Diameter Retort

	Nominal Material Bulk Density - lbs/cu. ft.				
900°F	5	10	15	20	25
% of Condensables	28.99	11.36	9.88	8.28	-
% of Combustables	17.71	6.90	5.93	4.86	-
1200°F					
% of Condensables	16.87	7.89	6.00	5.69	-
% of Combustibles	9.98	4.57	3.54	3.14	-
1500°F					
% of Condensables	19.57	7.73	7.22	6.48	2.12
% of Combustibles	11.68	3.92	3.72	3.39	1.10
1700°F					
% of Condensables	20.00	-	-	-	-
% of Combustibles	11.74	-	-	-	-

NOTE: Sulfur not determined

Table 8

Residue on Evaporation (103°C) of Condensables
(Percent by Weight)
18 Inch Diameter Retort

Nominal Material Bulk Density - lbs./cu. ft.

1200°F	5	10	15	20	25
% of Condensables	4.42	2.76	7.10	2.54	-
% of Combustibles	2.10	1.20	2.87	0.99	-
% Sulfur in Residue	0.48	0.57	0.44	0.58	-
% Sulfur in Combustibles	0.01	0.01	0.01	0.01	-
1500°F					
% of Condensables	6.66	2.50	4.27	1.22	-
% of Combustibles	2.89	1.05	1.70	0.44	-
% Sulfur in Residue	0.52	0.59	0.58	0.66	-
% Sulfur in Combustibles	0.19	0.01	0.01	0.01	-

concentrations exceeding 0.01%. These compounds were quantitated and are shown in Table 9.

The analysis of the liquid organics makes it possible to estimate more closely the energy available in the liquid of the condensables which, added to the previously determined caloric values of the residue on evaporation of the liquid (tars), gives a reasonable estimate of the energy available in the "crude vapor" (noncondensable gases, tars, and liquid organics). By using experimentally determined values of the specific heats of the individual components of typical San Diego refuse as shown in Table 10, Table 11 has been computed to show the Btu required to pyrolyze 1 pound of typical combustibles (19.77% free moisture). Btu available in the "hot vapor" evolved by the pyrolysis of 1 pound of the same typical combustibles were calculated and are shown in Table 12.

Table 13 shows the method used to derive the Btu available in the liquid organics from pyrolysis of a "typical refuse" in the 18 inch diameter retort. Liquid organic Btu values for condensables from the 4 inch diameter retort were calculated by difference from water analyses of the condensables using estimated values of 10,600 Btu/pound and a specific heat of 0.551.

Calculations indicate that, once raised to the selected pyrolyzing temperature, the process can be sustained by the combustion of the crude vapor alone providing the pyrolyzing equipment has had the proper overall thermal efficiency.

Table 9

ORGANICS IN LIQUID CONDENSABLES
(Percent by Weight)

18 Inch Diameter Retort

	1200°F				1500°F			
	Lbs/cu. ft. Material Bulk Density				Lbs/cu. ft. Material Bulk Density			
	5	10	15	20	5	10	15	20
Acetaldehyde	0.40	0.06	0.12	0.03	0.30	0.20	0.10	0.08
Acetone	0.55	0.23	0.34	0.21	0.47	0.30	0.29	0.22
Methylethylketone	0.13	0.15	0.10	0.05	0.14	0.22	0.19	0.06
Methanol	0.63	0.73	0.26	0.36	0.67	0.84	0.79	0.23
Chloroform	0.03	0.06	0.03	*	0.06	0.06	0.06	0.12
Toluene	0.04	*	*	*	0.09	*	*	*
Formic Acid	0.44	0.11	0.15	0.11	0.32	0.18	0.16	0.10
Furfural	0.22	0.12	0.70	0.06	0.23	0.24	0.08	0.07
Acetic Acid	0.04	0.08	0.04	*	0.06	0.07	0.04	*
Methylfurfural	0.21	0.12	0.09	0.04	0.19	0.12	0.08	0.04
Naphthalene	0.05	0.02	*	*	0.05	*	*	*
Methylnaphthalene	0.04	0.02	0.02	*	0.04	0.02	0.02	*
Phenol	0.20	0.17	0.19	0.21	0.16	0.15	0.19	0.13
Cresol	0.08	0.04	0.04	0.09	0.07	0.03	0.04	0.05
Total Organics	3.06	1.96	2.08	1.16	2.85	2.43	2.04	1.10
Water	96.58	97.32	92.87	92.87	89.30	94.50	97.92	91.38
Total Acct'd For	99.64	99.28	94.95	94.03	92.15	96.93	99.96	92.48

*Less than 0.01%

Table 10

Specific Heat of Typical San Diego Refuse

Constituent	% By Weight	Specific Heat (Btu/lb./°F)	Weighted Specific Heat (Btu/lb/°F)(Dry)
Paper	50.40	0.401	0.2021
Yard Trimmings	12.25	0.572	0.0701
Wood	7.96	0.500	0.0398
Rags	3.82	0.339	0.0129
Rubber	5.08	0.349	0.0177
Plastic	0.32	0.518	0.0017
Garbage	0.40	0.546	0.0022
Moisture	19.77	--	--
	100.00		0.3465

Table 11

Btu Required to Raise 1 Pound of "Typical Combustibles" from 60°F to Pyrolyzing Temperature.

Bases for calculations:

1) 1 pound "Typical Combustibles" consists of 0.1977 pounds water and 0.8023 pounds organics.

2) Steam table values of water enthalpy:

   a) 60° to 900°F - 1634 Btu/lb.

   b) 60° to 1200°F - 1790 Btu/lb.

   c) 60° to 1500°F - 1954 Btu/lb.

   d) 60° to 1700°F - 2065 Btu/lb.

3) Weighted specific heat of combustibles is 0.3465 Btu/lb/°F (Table 10)

4) "Hot Vapor" burned with stoichiometric air. Air requirement calculated from analysis of noncondensable gases.

For 4 Inch Diameter Retort

Nominal Material Bulk Density - lbs./cu. ft.

Temp. °F	5	10	15	20	25
900					
0.8023 lbs. comb.	234	234	234	234	
0.1977 lbs. water	323	323	323	323	
Stoichiometric Air	88	65	69	59	
Btu Required with 100% Thermal Efficiency	645	622	626	616	
Btu Required with 60% Thermal Efficiency	1075	1037	1043	1027	
1200					
0.8023 lbs. combustibles	317	317	317	317	
0.1977 lbs. Water	354	354	354	354	
Stoichiometric Air	227	225	247	254	
Btu Required with 100% Thermal Efficiency	898	896	918	925	
Btu Required with 60% Thermal Efficiency	1497	1493	1530	1542	

Table 11 (cont'd)

1500					
0.8023 lbs. combusts.	400	400	400	400	400
0.1977 lbs. Water	386	386	386	386	386
Stoichiometric Air	351	483	486	492	517
Btu Required with 100% Thermal Efficiency	1137	1269	1272	1278	1303
Btu Required with 60% Thermal Efficiency	1895	2115	2118	2130	2172
1700					
0.8023 lbs. Combustibles	456				
0.1977 lbs. Water	408				
Stoichiometric Air	361				
Btu Required with 100% Thermal Efficiency	1225				
Btu Required with 60% Thermal Efficiency	2042				

Table 11 (concl'd)

For 18 Inch Diameter Retort

Nominal Material Bulk Density - lbs./cu. ft.

	5	10	15	20
1200				
0.8023 lbs. combustibles	317	317	317	317
0.1977 lbs. water	354	354	354	354
Stoichiometric Air	334	372	418	413
Btu Required with 100% Thermal Efficiency	1005	1043	1089	1084
Btu Required with 60% Thermal Efficiency	1675	1738	1815	1807
1500				
0.8023 lbs. combustibles	400	400	400	400
0.1977 lbs. water	386	386	386	386
Stoichiometric Air	476	549	585	543
Btu Required with 100% Thermal Efficiency	1262	1335	1371	1329
Btu Required with 60% Thermal Efficiency	2103	2225	2285	2215

Table 12

Available Btu in Hot Vapor
per Pound of "Typical Combustibles"
4 Inch Diameter Retort

Nominal Material Bulk Density - lbs./cu. ft.

Temp. °F	5	10	15	20	25
900					
Gases	569	412	406	379	
Liquid Organics*	710	1163	1127	1055	
Tars	2163	644	556	538	
Total Available	3442	2219	2089	1972	
1200					
Gases	1045	1165	1117	1166	
Liquid Organics*	1683	1150	536	598	
Tars	1076	442	348	313	
Total Available	3804	2757	2001	2077	
1500					
Gases	1459	1843	1887	1800	1974
Liquid Organics*	955	720	691	612	383
Tars	1222	388	361	326	111
Total Available	3636	2951	2939	2738	2468
1700					
Gases	1415				
Liquid Organics*	622				
Tars	1192				
Total Available	3229				

*Calculated by difference from water analyses of condensables using estimated values of 10,600 Btu/lb. and a specific heat of 0.551.

Table 12 (cont'd)

Available Btu in Hot Vapor
per Pound of "Typical Combustibles"
18 Inch Diameter Retort

Temp. °F	Nominal Material Bulk Density - lbs./cu. ft. 5	10	15	20
1200				
Gases	1606	1789	1994	1972
Liquid Organics	148	89	86	49
Tars	240	139	435	127
Total Available	1994	2017	2515	2148
1500				
Gases	1853	2139	2298	2148
Liquid Organics	134	115	82	40
Tars	373	125	223	45
Total Available	2360	2379	2603	2233

Table 13

Btu Content of Liquid Organics
18 Inch Diameter Retort

1200°F - 5 lbs./cu. ft.	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
Condensables	0.4757						
Tars	0.0210						
Vols. - H_2O	0.4547						
Water	0.4391	96.58	-	-	-	-	-
Acetaldehyde	0.0018	0.40	11414	20.55	12.86	0.650	0.084
Acetone	0.0025	0.55	13246	33.12	17.86	0.528	0.094
Methanol	0.0029	0.63	9613	27.88	20.71	0.600	0.124
Methylethylketone	0.0006	0.13	14558	8.73	4.29	0.549	0.024
Chloroform	0.0001	0.03	1344	0.13	0.71	0.234	0.002
Toluene	0.0002	0.04	18278	3.66	1.43	0.470	0.007
Formic Acid	0.0020	0.44	2456	4.91	14.29	0.526	0.075
Furfural	0.0010	0.22	10491	10.49	7.14	0.418	0.030
Acetic Acid	0.0002	0.04	6288	1.26	1.43	0.468	0.007
Methylfurfural	0.0010	0.21	11516	11.52	7.14	0.522	0.037
Naphthalene	0.0002	0.05	17348	3.47	1.43	0.402	0.006
Methylnaphthalene	0.0002	0.04	17500	3.50	1.43	0.402	0.006
Phenol	0.0009	0.20	14034	12.63	6.43	0.561	0.036
Cresol	0.0004	0.08	14712	5.88	2.85	0.489	0.014
TOTAL	0.4531	99.64		147.73	100.00		0.546

Table 13 (cont'd)

	Weight of Constituent (lbs)	Components % of Vols. - H_2O	Components Btu/lb	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1200°F - 10 lbs./cu. ft.							
Condensables	0.4331						
Tars	0.0120						
Vols. - H_2O	0.4211						
Water	0.4098	97.32	-	-	-	-	-
Acetaldehyde	0.0003	0.06	11414	3.42	3.57	0.650	0.023
Acetone	0.0012	0.28	13246	15.90	14.29	0.528	0.075
Methanol	0.0031	0.73	9613	29.80	36.90	0.600	0.221
Methylethylketone	0.0006	0.15	14558	8.73	7.14	0.549	0.039
Chloroform	0.0003	0.06	1344	0.40	3.57	0.234	0.008
Toluene	0	0.01*	18278	0	0	0.470	0
Formic Acid	0.0005	0.11	2456	1.23	5.96	0.526	.031
Furfural	0.0005	0.12	10491	5.25	5.96	0.418	0.025
Acetic Acid	0.0003	0.08	6288	1.89	3.57	0.468	0.017
Methylfurfural	0.0005	0.12	11516	5.76	5.96	0.522	0.031
Naphthalene	0.0001	0.02	17348	1.73	1.19	0.402	0.005
Methylnaphthalene	0.0001	0.02	17500	1.75	1.19	0.402	0.005
Phenol	0.0007	0.17	14034	9.82	8.32	0.561	0.047
Cresol	0.0002	0.04	14712	2.94	2.38	0.489	0.012
TOTAL	0.4182	99.29		88.62	100.00		0.539

Table 13 (cont'd)

	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb.	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1200°F - 15 lbs/cu. ft.							
Condensables	0.4039						
Tars	0.0287						
Vol. Constits. -H_2O	0.3752						
Water	0.3484	92.87	-	-	-	-	-
Acetaldehyde	0.0005	0.12	11414	5.71	6.25	0.650	0.041
Acetone	0.0013	0.34	13246	17.22	16.25	0.528	0.086
Methanol	0.0010	0.26	9613	9.61	12.50	0.600	0.075
Methylethylketone	0.0004	0.10	14558	5.82	5.00	0.549	0.027
Chloroform	0.0001	0.03	1344	0.13	1.25	0.234	0.003
Toluene	0	0.01*	18278	0	0	0.470	0
Formic Acid	0.0006	0.15	2456	1.47	7.50	0.526	0.039
Furfural	0.0026	0.70	10491	27.28	32.50	0.418	0.136
Acetic Acid	0.0002	0.04	6288	1.26	2.50	0.468	0.012
Methylfurfural	0.0003	0.09	11516	3.45	3.75	0.522	0.020
Naphthalene	0	0.01*	17348	0	0	0.402	0
Methylnaphthalene	0.0001	0.02	17500	1.75	1.25	0.402	0.005
Phenol	0.0007	0.19	14034	9.82	8.75	0.561	0.049
Cresol	0.0002	0.04	14712	2.94	2.50	0.489	0.012
TOTAL	0.3564	94.97		86.46	100.00		0.505

Table 13 (cont'd)

	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb.	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1200°F - 20 lbs./cu. ft.							
Condensables	0.3895						
Tars	0.0099						
Vols. Constits. - H_2O	0.3796						
Water	0.3525	92.87	-	-	-	-	-
Acetaldehyde	0.0001	0.03	11414	1.14	2.27	0.650	0.015
Acetone	0.0008	0.21	13246	10.60	18.18	0.528	0.096
Methanol	0.0014	0.36	9613	13.46	31.81	0.600	0.191
Methylethylketone	0.0002	0.05	14558	2.91	4.55	0.549	0.025
Chloroform	0	0.01*	1344	0	0	0.234	0
Toulene	0	0.01*	18278	0	0	0.470	0
Formic Acid	0.0004	0.11	2456	0.98	9.09	0.526	0.048
Furfural	0.0002	0.06	10491	2.10	4.55	0.418	0.019
Acetic Acid	0	0.01*	6288	0	0	0.468	0
Methylfurfural	0.0002	0.04	11516	2.30	4.55	0.522	0.024
Naphthalene	0	0.01*	17348	0	0	0.402	0
Methylnaphthalene	0	0.01*	17500	0	0	0.402	0
Phenol	0.0008	0.21	14034	11.23	18.18	0.561	0.102
Cresol	0.0003	0.09	14712	4.41	6.82	0.489	0.033
TOTAL	0.3569	94.08		49.13	100.00		0.533

Table 13 (cont'd)

	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb.	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1500°F - 5 lbs./cu. ft.							
Condensables	0.4339						
Tars	0.0289						
Volatiles -H_2O	0.4050						
Water	0.3617	89.30	-	-	-	-	-
Acetaldehyde	0.0012	0.30	11414	13.70	10.43	0.650	0.068
Acetone	0.0019	0.47	13246	25.17	16.52	0.528	0.087
Methanol	0.0006	0.14	9613	5.77	5.22	0.600	0.031
Methylethylketone	0.0027	0.67	14558	39.31	23.48	0.549	0.129
Chloroform	0.0002	0.06	1344	0.27	1.74	0.234	0.004
Toluene	0.0004	0.09	18278	7.31	3.48	0.470	0.016
Formic Acid	0.0013	0.32	2456	3.19	11.30	0.526	0.059
Furfural	0.0009	0.23	10491	9.44	7.83	0.418	0.033
Acetic Acid	0.0002	0.06	6288	1.26	1.74	0.468	0.008
Methylfurfural	0.0008	0.19	11516	9.21	6.96	0.522	0.036
Naphthalene	0.0002	0.05	17348	3.47	1.74	0.402	0.007
Methylnaphthalene	0.0002	0.04	17500	3.50	1.74	0.402	0.007
Phenol	0.0006	0.16	14034	8.42	5.22	0.561	0.029
Cresol	0.0003	0.07	14712	4.41	2.60	0.489	0.013
TOTAL	0.3732	92.15		134.43	100.00		0.527

Table 13 (cont'd)

	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb.	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1500°F - 10 lbs./cu. ft.							
Condensables	0.4205						
Tars	0.0105						
Volatiles - H_2O	0.4100						
Water	0.3875	94.50	-	-	-	-	-
Acetaldehyde	0.0008	0.20	11414	9.13	8.17	0.650	0.053
Acetone	0.0012	0.30	13246	15.90	12.25	0.528	0.065
Methanol	0.0009	0.22	9613	8.65	9.18	0.600	0.055
Methylethylketone	0.0034	0.84	14558	49.50	34.69	0.549	0.190
Chloroform	0.0002	0.06	1344	.27	2.04	0.234	0.005
Toluene	0	0.01*	18278	0	0	0.470	0
Formic Acid	0.0007	0.18	2456	1.72	7.15	0.526	0.038
Furfural	0.0010	0.24	10491	10.49	10.20	0.418	0.043
Acetic Acid	0.0003	0.07	6288	1.89	3.06	0.468	0.014
Methylfurfural	0.0005	0.12	11516	5.76	5.10	0.522	0.027
Naphthalene	0	0.01*	17348	0	0	0.402	0
Methylnaphthalene	0.0001	0.02	17500	1.75	1.02	0.402	0.004
Phenol	0.0006	0.15	14034	8.42	6.12	0.561	0.034
Cresol	0.0001	0.03	14712	1.47	1.02	0.489	0.005
TOTAL	0.3973	96.95		114.95	100.00		0.533

Table 13 (cont'd)

	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb.	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1500°F - 15 lbs./cu. ft.							
Condensables	0.3990						
Tars	0.0170						
Volatiles - H_2O	0.3820						
Water	0.3741	97.92	-	-	-	-	-
Acetaldehyde	0.0004	0.10	11414	4.57	5.13	0.650	0.033
Acetone	0.0011	0.29	13246	14.57	14.10	0.528	0.074
Methanol	0.0007	0.19	14558	10.19	8.97	0.600	0.054
Methylethylketone	0.0030	0.79	9613	28.84	38.46	0.549	0.211
Chloroform	0.0002	0.06	1344	0.27	2.56	0.234	0.006
Toluene	0	0.01*	18278	0	0	0.470	0
Formic Acid	0.0006	0.16	2456	1.47	7.69	0.526	0.040
Furfural	0.0003	0.08	10491	3.15	3.86	0.418	0.016
Acetic Acid	0.0002	0.04	6288	1.26	2.56	0.468	0.012
Methylfurfural	0.0003	0.08	11516	3.45	3.86	0.522	0.020
Naphthalene	0	0.01*	17348	0	0	0.402	0
Methylnaphthalene	0.0001	0.02	17500	1.75	1.28	0.402	0.005
Phenol	0.0007	0.19	14034	9.82	8.97	0.561	0.050
Cresol	0.0002	0.04	14712	2.94	2.56	0.489	0.013
TOTAL	0.3819	99.98		82.28	100.00		0.534

Table 13 (concl'd)

	Weight of Constituent (lbs.)	Components % of Vols. - H_2O	Components Btu/lb.	Btu Contribution of Volatiles	% of Vols.	Specific Heat Btu/lb./°F	Specific Heat Contribution of Volatiles
1500°F - 20 lbs./cu. ft.							
Condensables	0.3646						
Tars	0.0044						
Volatiles - H_2O	0.3602						
Water	0.3292	91.38	-	-	-	-	-
Acetaldehyde	0.0003	0.08	11414	3.42	7.50	0.650	0.049
Acetone	0.0008	0.22	13246	10.60	20.00	0.528	0.106
Methanol	0.0002	0.06	14558	2.91	5.00	0.600	0.030
Methylethylketone	0.0008	0.23	9613	7.69	20.00	0.549	0.110
Chloroform	0.0004	0.12	1344	0.54	10.00	0.234	0.023
Toluene	0	0.01*	18278	0	0	0.470	0
Formic Acid	0.0004	0.10	2456	0.98	10.00	0.526	0.053
Furfural	0.0003	0.07	10491	3.15	7.50	0.418	0.031
Acetic Acid	0	0.01*	6288	0	0	0.468	0
Methylfurfural	0.0001	0.04	11516	1.15	2.50	0.522	0.013
Naphthalene	0	0.01*	17348	0	0	0.402	0
Methylnaphthalene	0	0.01*	17500	0	0	0.402	0
Phenol	0.0005	0.13	14034	7.02	12.50	0.561	0.070
Cresol	0.0002	0.05	14712	2.94	5.00	0.489	0.024
TOTAL	0.3332	92.52		40.40	100.00		0.509

Char

The solid residue remaining after pyrolysis is an impure carbon, the impurities being various inorganics and inert materials not amenable to pyrolysis. It is black in color and, if the retort charge is undisturbed during pyrolysis, it retains the general configuration and apparent volume of the original retort charge. It is quite friable and readily reduces to small granules and powder the bulk density of which approximates 16 pounds per cubic foot.

The char from pyrolysis contains, in addition to carbon (the end product of the destructive distillation of organic material) any other materials not amenable to the pyrolysis process which may have been included in the original material. These could be glass, metal and dirt.

Table 14 shows the results of the proximate analyses of the char from the 4 inch diameter retort and Table 15 shows the results from the 18 inch diameter retort.

It was noted that the percent ash in the char varied quite widely. Chemical analyses of some of the high percentage ashes showed them to be predominately silicates. The concentration of the silicates varied directly with the percent ash. Investigation into the makeup of the original retort charge showed that more slick magazine paper was used in compositing the retort charges of high ash content than those of low ash content. It was reasoned that the clay filler used in slick magazine paper could account for the differing ash contents found by proximate analysis. This has been confirmed by others.(5)

Table 14

Proximate Analysis of Pyrolysis Char
(ASTM D271-58 (dry basis))
4 Inch Diameter Retort

Nominal Material Bulk Density - lbs./cu. ft.

900°F	5	10	15	20	25
Volatile Matter, %	21.81	22.66	21.77	21.65	
Fixed Carbon %	70.48	66.07	63.34	68.20	
Ash, %	7.71	11.27	14.89	10.15	
Btu per Pound	12,120	11,830	11,530	12,140	
1200°F					
Volatile Matter, %	15.05	11.81	11.22	10.74	
Fixed Carbon, %	70.67	72.99	72.74	72.34	
Ash, %	14.28	15.20	16.04	16.92	
Btu per Pound	12,280	11,830	11,890	11,560	
1500°F					
Volatile Matter, %	8.13	7.91	7.64	6.33	7.67
Fixed Carbon, %	79.05	78.79	76.53	75.27	78.67
Ash, %	12.82	13.30	15.83	18.40	13.66
Btu per Pound	11,540	11,860	11,430	11,270	11,980
1700°F					
Volatile Matter, %	8.30				
Fixed Carbon, %	77.23				
Ash, %	14.47				
Btu per Pound	11,400				

Note: Sulfur not determined

Table 15

Proximate Analysis of Pyrolysis Char
(ASTM D271-58 (dry basis))
18 Inch Diameter Retort

	Nominal Meterial Bulk Density - lbs./cu. ft.			
1200°F	5	10	15	20
Volatile Matter, %	3.31	5.18	4.03	5.33
Fixed Carbon, %	77.46	77.14	70.56	70.69
Ash, %	19.23	17.68	25.41	23.98
Btu per Pound	11,620	11,400	10,520	11,490
Sulfur in Char, %	0.57	0.48	1.04	0.99
Sulfur per lb. Combustibles, %	0.13	0.12	0.50	0.25
1500°F				
Volatile Matter, %	3.08	4.24	3.36	3.25
Fixed Carbon, %	95.77	80.79	71.16	71.59
Ash, %	1.15	14.97	25.48	25.16
Btu per Pound	14,170	12,090	10,920	11,010
Sulfur in Char, %	0.48	0.33	1.25	1.06
Sulfur per lb. Combustibles, %	0.12	0.08	0.29	0.25

Under certain operational procedures, the volume reduction which can be achieved when processing municipal solid wastes by pyrolysis is of as great a magnitude as that accomplished by incineration. There are, however, some materials in municipal refuse which cause operating problems when incinerated. These materials are metals and glass and, in some instances, plastics.

Kaiser and Trantwein say, "Important for high furnace availability is the prevention of massive formations of sintered glass, ash and metal on the lower walls of large incinerators".(6) Such deposits restrict the action of the stoker grates, impede the flow of refuse, cause the bed to thicken ahead of the deposits and to avalanche into the void created behind the deposit zone. After cooling the furnace 5-8 hours, the deposited mass usually loosened at the wall and could be pried off. It was held together by wires, pipe and metal imbedded in it. The glass was softened and deformed by the heat and adhered to the silicon carbide furnace wall.(7)

To investigate the effect of pyrolysis on glass bottles, runs were made at 1500°F using "typical refuse" adjusted to a 10% garbage content at 15 lbs./cu. ft. bulk density. Throwaway bottles were packed in the center of the retort charge. Pyrolyzing time was 9.35 hours. Figure 7 is a photograph of "before" and "after" pyrolysis. Although the glass deformed and softened sufficiently to permit the carbonaceous char from pyrolysis to adhere to its surface, it did not soften to the extent that it became fluid and flowed throughout the mass of material being pyrolyzed. No difficulty was experienced in removing it from the retort after pyrolysis.

Figure 7

Glass bottles before and after pyrolysis. Furnace at 1500°F. for 9.35 hours.

Glass bottles before and after pyrolysis.

Figure 8

Furnace at 1200°F for 11.5 hrs.

Figure 9

At 1200°F a heat was run which included a bottle having an embossed design around its circumference. Figure 8 and Figure 9 show that after pyrolyzing at 1200°F for 11.5 hours, there was softening and deformation of the glass but when the bottles were removed from the retort after pyrolyzing, the embossed design was still recognizable.

Run No. 190 was made using plated cans. Pyrolyzing was at 1500°F for 6 hours. Figure 10 shows the retort before bolting on the lid and lowering into the furnace. Figure 11 is the appearance of the cans after pyrolyzing and Figure 12 is a picture of the cans after removal from the retort.

The cans were blackened, lost any organic coating (paper labels, paint, etc.) and also some solder used in the seams during fabrication.

It is felt that the small amount of glass and metal in the classification of San Diego refuse would not be sufficient to cause operating problems.

(A study of the typical physical and mechanical properties of plastics(8) shows the flammability of a significant number of plastics as self-extinguishing). This implies that they are difficultly oxidizable. Modorsky and Straus (9) found that some plastics vaporize completely when pyrolyzed in a vacuum or in a neutral gas and that highly crosslinked polymers volatilize partially and leave a stable carbonaceous residue.(10)

Several plastic materials were pyrolyzed for 35 minutes at 1500°F. The results are listed in Table 16. Figures 13 and 14 show polystyrene before and after pyrolysis.

Figure 10

Plated cans before pyrolysis

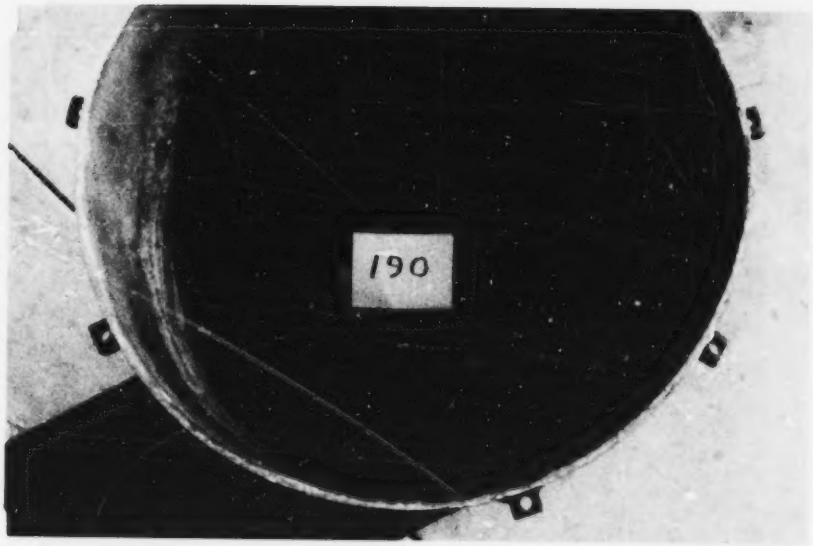


Figure 11

Plated cans after pyrolysis.
Before removal from retort.
Furnace at 1500°F. for 6 hours

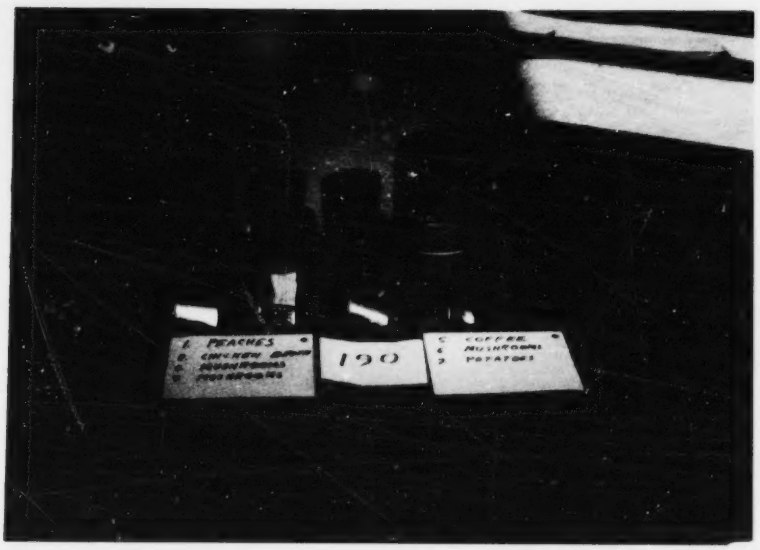


Figure 12

Plated cans of Figure 11 after removal from retort. Furnace at 1500°F. for 6 hours.

Table 16

PLASTICS PYROLYZED AT 1500°F
PYROLYSIS TIME - 35 MINUTES

Material	% By Weight Volatilized
Polyethylene	95.53
Polystyrene	90.42
Polyvinylchloride	71.01
Nylon	84.16
Polypropylene	91.06
Polyurethane	80.34
Acrylic	96.44
Saran Wrap	64.72

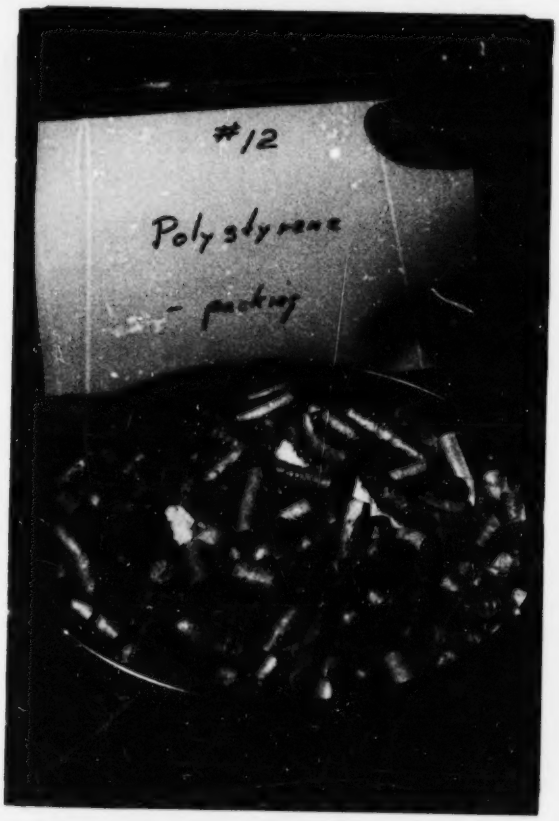


Figure 13

Polystyrene plastic before pyrolysis

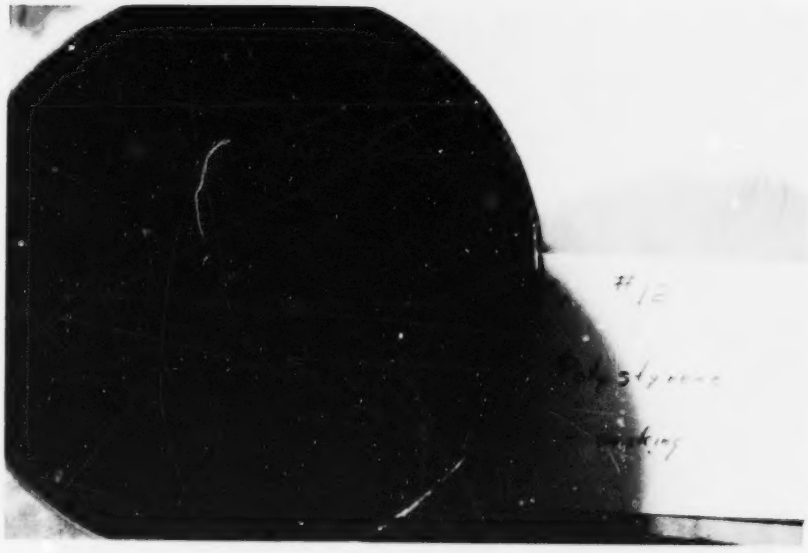


Figure 14

Polystyrene plastic after pyrolysis

Furnace at 1500°F. for 35 minutes

Three runs were made using the 18 inch diameter retort for pyrolyzing and adjusting the retort charge to contain 10% garbage. Using the "% As Received" and the "% Moisture" from Table 1, the classification and specific heat of the adjusted charge was as shown in Table 17.

The retort charge was made to 15 lbs/cu. ft. and pyrolyzing was at 1500°F.

Results obtained were compared with those from a "typical" sample in Table 18.

Adjustment of "Typical San Diego Residential Pickup" to contain 10% garbage resulted in increasing moisture from 19.77% to 23.89% by weight. When pyrolyzed at 1500°F, the 10% garbage sample (15 lbs./cu.ft.) yielded about 10% by volume more noncondensable gases per pound of charged material than did the "Typical San Diego Combustibles" of the same 15 lbs/cu. ft. bulk density pyrolyzed at the same temperature. The most substantial increases are in the combustible gases, hydrogen (H_2) and methane (CH_4). The combustible gas, carbon monoxied (CO), shows a slight increase and the noncombustible gas carbon dioxide (CO_2) shows a marked decrease. The combination of these two factors, e.g. the increase in volume of combustible gases together with the volume decrease of the noncombustible gas, yields an off-gas having a higher Btu per cubic foot and also a higher Btu per pound of material pyrolyzed.

The presence of the additional moisture lengthens the pyrolysis time to the extent that the pounds pyrolyzed per hour drop from 20.44 for the "Typical San Diego Combustibles" to 13.54 for the 10% garbage samples and the pyrolyzing time in

Table 17

Composition and Specific Heat of "Typical San Diego Residential Pickup" When the Garbage Content of the "As Received" Refuse is Assumed as 10%.

Constituent	% On Dry Basis Without Metal & Glass	Specific Heat Btu/lb./°F	Weighted Specific Heat Btu/lb./°F
Paper	44.96	0.401	0.1803
Yard trimmings	10.93	0.572	0.0625
Wood	7.11	0.500	0.0356
Rags	3.39	0.339	0.0115
Rubber	4.51	0.349	0.0157
Plastic	0.28	0.518	0.0015
Garbage	4.93	0.546	0.0269
Moisture	23.89	-	-
	100.00		0.3340

Table 18

Material Balance

	Gas	Condensables	Char	Accounted For
"Typical" Sample	40.42%	39.90%	23.17%	103.48%
With 10% Garbage	36.88%	40.59%	21.17%	98.64%

Noncondensable Gases

Cubic Feet/lb. of Material

	CO_2	CO	CH_4	H_2	C_2H_6	C_2H_4	Total
"Typical" Sample	1.640	1.823	0.874	2.239	0.022	0.091	6.689
With 10% Garbage	1.180	1.935	1.042	3.102	0.027	0.090	7.376

	Noncond. Gas-Btu per Cu. Ft.	Noncond. Gas-Btu per lb. Mat'l	Lbs/Mat'l Pyrolyzed per hour	Pyrolyzing Time Minutes/lb.
"Typical" Sample	343	2298	20.44	2.94
With 10% Garbage	374	2757	13.54	4.43

Btu Available in "Hot Vapor"

	"Typical Sample"	10% Garbage
Gases	2298	2757
Tars	223	149
Liquid Organics	82	78*
Total	2603	2984

*Estimated

Btu Requirement/lb. Material:

	"Typical" Sample	With 10% Garbage
Combustibles	400	366
Moisture	386	467
Stoichiometric Air	585	708
With 100% Thermal Efficiency	1371	1541
With 60% Thermal Efficiency	2285	2569

minutes per pound goes from 2.94 for "Typical San Diego Combustibles" to 4.43 for the 10% garbage sample - an increase of some 50%.

Volume Reduction

Although the fill classification investigation showed that less than 50% by weight of the solid municipal wastes of San Diego are amenable to the pyrolysis process, nevertheless considerable reduction of fill space consumption could be effected if pyrolysis were to be integrated into the San Diego solid waste disposal program.

Table 19 shows the percentage of fill space used in one year when disposing of San Diego's solid wastes by four alternate methods. This Table has been computed on the basis of experimental results from the 4 inch diameter retort. Figure 15 is the graphic presentation of Table 19.

Table 20 is comparable to Table 17, but has been computed from the experimental results from the 18 inch diameter retort. Figure 16 is the graphic presentation of Table 20.

During the course of a feasibility study on the baling of municipal refuse, funded jointly by the Office of Solid Wastes and the City of San Diego Public Works Department (11), investigations were carried out with differing amounts of water and compacting equipment. The purpose was to determine the optimum in-place bulk density obtainable with unprocessed solid municipal wastes. The maximum compaction obtained was 1383 pounds per cubic yard (51 pounds per cubic foot) when using a Pactor Model 3-40 diesel "Trashmaster".(12)

Table 19

Estimated Fill Space Usage at San Diego
When Using Alternative Disposal Methods.
(Based on 4 Inch Diameter Retort Values)

Description of Method

Alternate 1 - Present Practice (cover unprocessed wastes)

Alternate 2 - Pyrolyze Combustibles @ 1500°F. Produce char (20% by weight of Combustibles), bury char and inerts in fill site.

Alternate 3 - Pyrolyze Combustibles @ 1500°F. Produce char as in Alternate 2, incinerate char produced. Bury ash and inerts in fill site.

Alternate 4 - Pyrolyze combustibles @ 1500°F. Produce char as in Alternate 2. Market char - bury inerts in fill site.

Key Values Used

Wastes Disposed	Tons	Cubic Yards
1) Construction Debris and Fill Dirt (49.33%) (120 lbs/ft3)	259,969	160,475
2) Glass (4.16%) (60lbs./ft3)	21,923	27,065
3) Metals (3.82%) (128 lbs/ft3)	20,131	11,596
4) Combustibles (42.69%) (13lbs/ft3)	224,977	564,632
5) Total Wastes Disposed (51 lbs/ft3)	527,000	763,768
6) Construction Debris and Fill Dirt	% By Weight 49.33	Density 120 lbs/ft3
7) Glass (including 60% voids)	4.16	60 lbs/ft3
8) Metals (including 60% voids)	3.82	128 lbs/ft3
Total Unaffected by Pyrolysis	57.31	67 lbs/ft3
9) Combustibles Amenable to Pyrolysis	42.69	13 lbs/ft3
Total	100.00	51 lbs/ft3
10) Char from Pyrolysis of Combustibles		15 lbs/ft3
11) Ash from Incineration of Pyrolysis Char		35 lbs/ft3

Table 19 (concl'd)

Methods of Disposal	Tons	Cu. Yards	Fill Space Use
Alternate 1.			
Present Practice (No Pyrolysis)	527,000	763,768	100 %
Alternate 2.			
Produce Char (0.20x224,977 tons)	44,995	222,198	
Inerts Unaffect by Pyrolysis	302,023	199,136	
Total to Dispose	347,018	421,334	55.1 %
Alternate 3.			
Incinerate Char (0.1480x44,995 tons)	6,660	14,095	
Inerts Unaffected by Pyrolysis	302,023	199,136	
Total to Dispose	308,683	213,231	27.9 %
Alternate 4.			
Market Char	0	0	
Inerts Unaffected by Pyrolysis	302,023	199,136	
Total to Dispose	302,023	199,136	26.1 %

PYROLYSIS OF SAN DIEGO SOLID WASTES

EFFECT ON ANNUAL FILL SPACE USAGE

ANNUAL TONNAGE - 527,000 TONS

4" DIAMETER RETORT

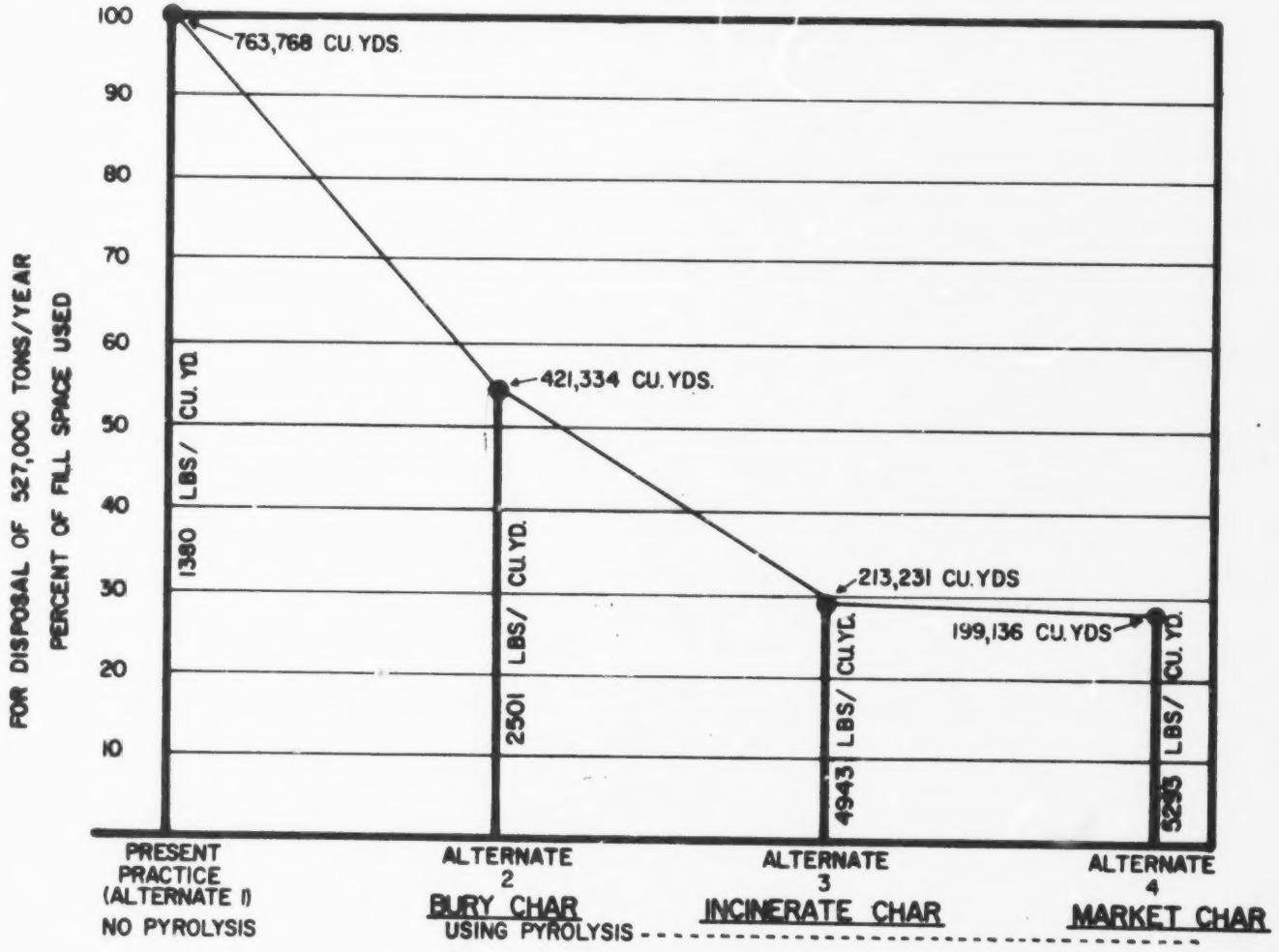


FIGURE 15

Table 20

Estimated Fill Space Usage at San Diego When Using Alternative Disposal Methods

(Based on 18 Inch Diameter Retort Values)

Methods of Disposal

Alternate 1.	Tons	Cu. Yards	Fill Space Used
Present Practice (No Pyrolysis)	527,000	763,768	100 %
Alternate 2.			
Produce Char (0.2384x224,977 tons)	53,635	264,864	
Inerts Unaffected by Pyrolysis	302,023	199,136	
Total to Dispose	355,658	464,000	60.8 %
Alternate 3.			
Incinerate Char (0.1480x53,635 tons)	7,938	16,800	
Inerts Unaffected by Pyrolysis	302,023	199,136	
Total to Dispose	309,961	215,936	28.3 %
Alternate 4.			
Market Char	0	0	
Inerts Unaffected by Pyrolysis	302,023	199,136	
Total to Dispose	302,023	199,136	26.1 %

PYROLYSIS OF SAN DIEGO SOLID WASTES

EFFECT ON ANNUAL FILL SPACE USAGE

ANNUAL TONNAGE-527,000 TONS

18" DIAMETER RETORT

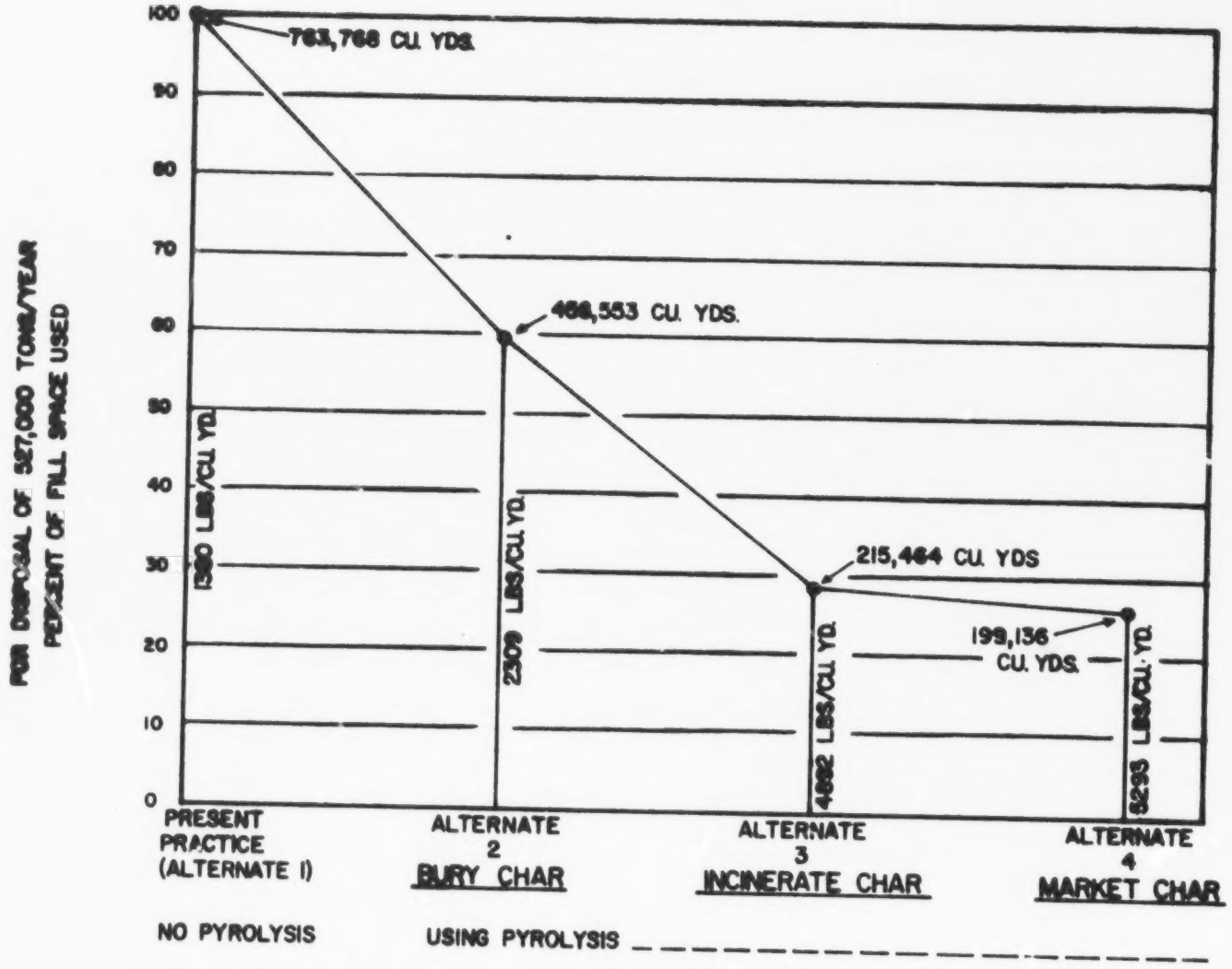


FIGURE 16

IV. DISCUSSION:

At temperatures of 1200°F and 1500°F, the volume of non-condensable gases evolved per pound of "typical combustibles" varies directly with the bulk density of the material pyrolyzed. The volume of these evolved gases peaks out at a 15 lbs./cu.ft. material bulk density, but when pyrolyzing material of 20 lbs/cu.ft. at these same temperatures, the gas volume is apparently reduced. The amount of reduction is quite small, in fact, it is small enough to be considered within the limits of experimental error except that it consistently occurs from 15 to 20 lbs/cu.ft. material bulk density at 900°F, 1200°F, and 1500°F, in the 4 inch diameter retort and at 1200°F and 1500°F in the 18 inch diameter retort. When pyrolyzing at 900°F, gas volume evolved per pound of "typical combustibles" varies inversely with material bulk density.

In choosing an "optimum" point at which to pyrolyze, the following parameters have been used:

1) Temperature of pyrolysis.
2) Bulk density of material pyrolyzed.
3) Cubic feet of gas evolved per pound of "typical combustibles.
4) Btu per cubic foot of the evolved gas.
5) Btu of gases evolved by the pyrolysis of one pound of "typical combustibles".
6) Pyrolyzing rate expressed either as pounds pyrolyzed per hour or as minutes required to pyrolyze one pound of "typical combustibles".

These parameters have been summarized and are presented in Table 21 and Table 22. Inspection of these two tables shows that the production rate, expressed as pounds pyrolyzed per hour, is in every case many fold greater when using an 18 inch diameter

Table 21

EVALUATION PARAMETERS

4 Inch Diameter Retort

Temp. °F	Lbs/Cu. Ft. Material Bulk Density	Cu. Ft. Gas Evolved per Lb. Combust's.	Btu/Cu. Ft. of Evolved Gases	Evolved Gases Btu/lb. Combust's	Pounds Pyrolyzed Per Hour	Minutes to Pyrolyze 1 Pound
900	5	1.90	300	569	0.89	68.41
	10	1.46	283	412	0.94	64.45
	15	1.47	280	410	0.98	61.71
	20	1.38	286	395	1.35	47.34
1200	5	2.78	376	1045	1.46	42.72
	10	2.98	392	1165	1.73	34.87
	15	3.03	369	1117	1.85	32.90
	20	3.01	387	1166	2.28	26.52
1500	5	4.25	344	1459	2.71	29.04
	10	4.71	391	1843	3.06	19.60
	15	4.85	389	1887	3.01	20.82
	20	4.62	389	1800	3.46	17.33
	25	4.95	399	1976	3.43	17.57
1700	5	4.03	351	1414	2.42	29.53

Table 22

Evaluation Parameters

18 Inch Diameter Retort

Temp. °F	Lbs/Cu. Ft. Material Bulk Density	Cu. Ft. Gas Evolved per Lb. Combust's.	Btu/Cu. Ft. of Evolved Gases	Evolved Gases Btu/lb. Combust's.	Pounds Pyrolyzed Per Hour	Minutes To Pyrolyze 1 Pound
1200	5	4.46	360	1606	9.75	6.18
	10	4.83	370	1789	12.50	4.79
	15	5.43	367	1994	14.55	4.13
	20	5.30	372	1972	12.66	4.76
1500	5	5.27	352	1853	13.39	4.48
	10	6.09	351	2139	17.39	3.45
	15	6.69	343	2298	20.44	2.94
	20	6.50	331	2148	19.45	3.09

retort than when using one of a 4 inch diameter. The highest rate of throughput being at 15 lbs./cu.ft. material bulk density with a pyrolyzing temperature of 1500°F. Table 22 also shows that at 1500°F/15 lbs/cu.ft. bulk density the maximum volume of noncondensable gases is evolved per pound of "typical combustibles" which, in turn, also provides the maximum Btu per pound of "typical combustibles". Table 12 shows that at 1500°F/15 lbs/cu.ft. the hot vapor (noncondensable gases, tars and liquid organics) from one pound of "typical combustibles" is calculated to contain 2603 Btu. Table 11 shows that the theoretical Btu required to pyrolyze one pound of "typical combustibles at 1500°F and 15 lbs./cu.ft. is 2285 Btu if the overall thermal efficiency of the equipment is 60%. Based on these computations, the process would, at this point, be self-sustaining.

Pyrolysis is defined as the "breaking down of complex materials into simpler units by use of heat"(14). The reaction products result from not only primary, but also secondary and tertiary reactions(15).

It is reasonable to assume that were only a primary reaction involved, then the amounts of pyrolytic decomposition products from samples of relatively similar composition would not vary too widely regardless of the bulk density of the material pyrolyzed providing the pyrolysis is done at the same temperature. The fact that a great variation does exist is shown by Table 23 and Figure 17, which is a bar chart built from the data of that table.

Schaffer (16) states "Organic components of the ablating

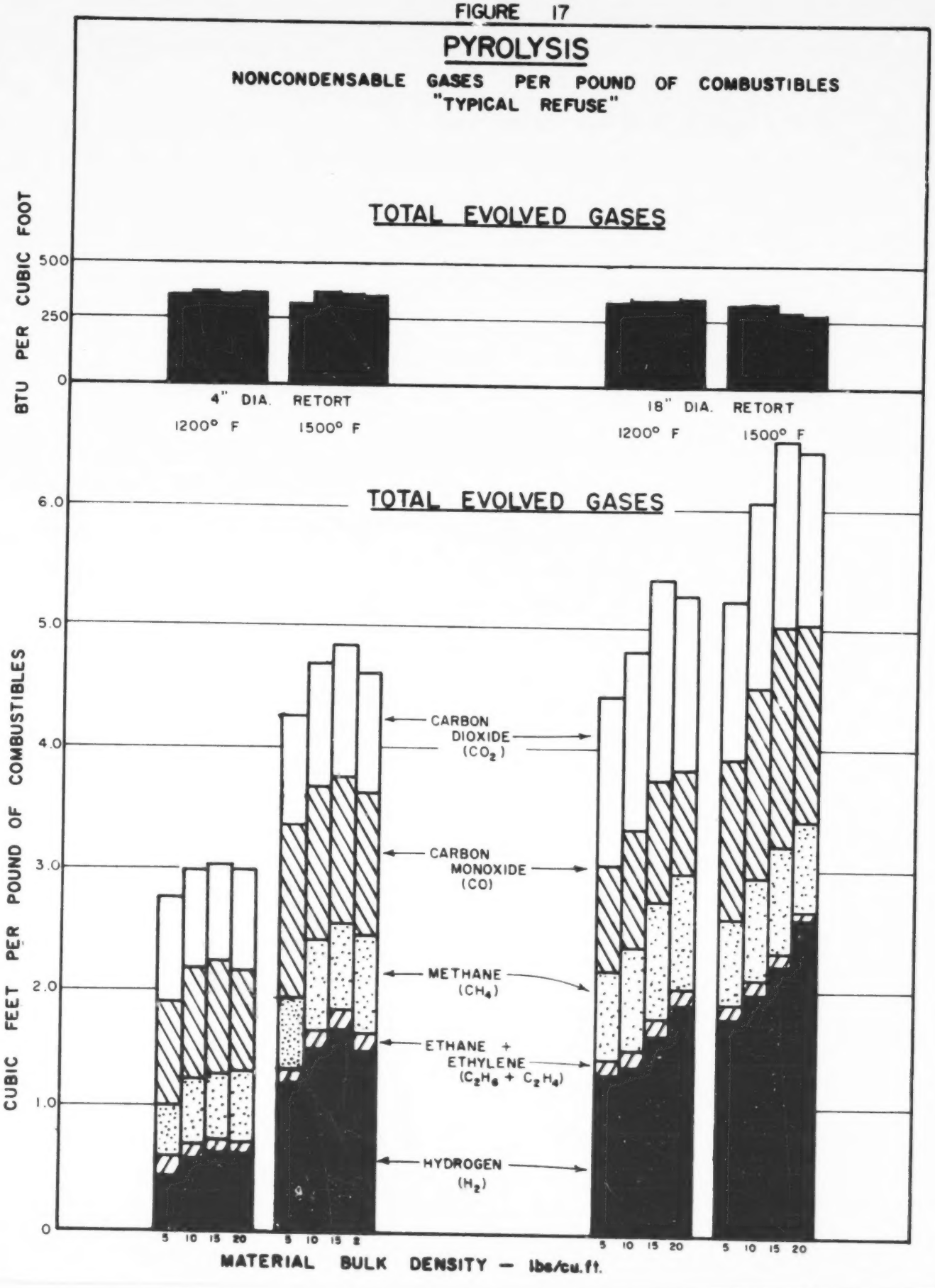
Table 23

Comparative Cubic Feet
Noncondensable Gases/lb. of Combustibles
4" & 18" Diameter Retorts

Nominal Material Bulk Density (lbs./cu. ft.)

1200°F	5		10		15		20	
	4"	18"	4"	18"	4"	18"	4"	18"
Carbon Dioxide (CO_2)	0.884	1.396	0.786	1.470	0.788	1.666	0.819	1.440
Carbon Monoxide (CO)	0.849	0.864	0.908	0.968	0.938	0.981	0.863	0.867
Methane (CH_4)	0.443	0.731	0.570	0.863	0.543	0.982	0.565	0.945
Hydrogen (H_2)	0.461	1.332	0.594	1.398	0.665	1.662	0.643	1.916
Ethane (C_2H_6)	0.085	0.042	0.057	0.041	0.055	0.040	0.068	0.042
Ethylene (C_2H_4)	0.061	0.091	0.060	0.093	0.042	0.100	0.048	0.087
Total	2.783	4.456	2.975	4.833	3.031	5.431	3.006	5.297
1500°F								
Carbon Dioxide (CO_2)	0.874	1.328	1.017	1.552	1.064	1.640	0.983	1.446
Carbon Monoxide (CO)	1.448	1.323	1.282	1.550	1.206	1.823	1.161	1.617
Methane (CH_4)	0.583	0.707	0.729	0.869	0.741	0.874	0.808	0.740
Hydrogen (H_2)	1.212	1.791	1.513	1.998	1.688	2.240	1.508	2.617
Ethane (C_2H_6)	0.033	0.039	0.053	0.029	0.046	0.021	0.048	0.013
Ethylene (C_2H_4)	0.095	0.083	0.120	0.090	0.109	0.091	0.113	0.062
Total	4.245	5.271	4.714	6.088	4.854	6.689	4.621	6.495

FIGURE 17


PYROLYSIS
NONCONDENSABLE GASES PER POUND OF COMBUSTIBLES
"TYPICAL REFUSE"
TOTAL EVOLVED GASES
BTU PER CUBIC FOOT
500
250
0
4" DIA. RETORT
1200° F
1500° F
18" DIA. RETORT
1200° F
1500° F
TOTAL EVOLVED GASES
CUBIC FEET PER POUND OF COMBUSTIBLES
6.0
5.0
4.0
3.0
2.0
1.0
0
CARBON DIOXIDE (CO_2)
CARBON MONOXIDE (CO)
METHANE (CH_4)
ETHANE + ETHYLENE ($C_2H_6 + C_2H_4$)
HYDROGEN (H_2)
5 10 15 20
MATERIAL BULK DENSITY — lbs/cu.ft.

material are depolymerized or pyrolyzed into various gaseous products such as hydrogen, carbon monoxide, methane, ethylene, acetylene, water, and various hydrocarbon fragments...Thermal degredation of the organic material may take place with the formation of a rigid, nonuniform, and porous carbonaceous material. Gases formed in the substrate pass through this surface layer, absorb heat, and minimize further internal heat transfer...As more polymer degrades, the char layer increases in thickness at the expense of the unreacted polymer below it. While the gases pass through the char residue, the char becomes hotter and the degradation vapors are exposed to higher temperatures. As a result, they may experience further degradation or pyrolysis".

This pheonomenon could well explain the differences in noncondensable gases and condensables observed at differing material bulk densities in the 4 and 18 inch diameter retorts.

The amount of char formed increases with the amount of material pyrolyzed which, in turn, increases with the bulk density of the material undergoing pyrolysis. With more char formed, the degradation vapors from the polymer layer beneath the char layer must pass through a continually thickening layer of char and their time of exposure to the cracking and/or dehydrogenating action of the hot char lengthens.

Increasing the retort diameter from 4 inches to 18 inches accomplishes the same result even with retort charges of the same bulk density.

Although no large capacity pyrolyzing installations are in operation, there are figures available from which it is possible to deduce a very rough estimate of the approximate capital cost

comparison between incineration and pyrolysis.

Rogus(13) presented the capital cost of the refuse incineration equipment in use in six western European municipalities, Montreal, Canada, and New York City, expressed as both total capital cost and unit capital costs per ton per day. Unit capital costs per ton per day varied from a low of $6000 at Rotterdam, Holland, to a high of $16,000 at Vienna, Austria. Rogus reported a unit cost of $8000 per ton per day for the six New York City incinerators.

The capital cost of a large scale installation of continuous operation pyrolysis retorts processing solid municipal wastes is unknown, for at this time none is in operation. In 1965, the City of San Diego received a proposal from a Southern California company to furnish certain items of a continuous pyrolysis installation, not including enclosure buildings, storage silos for the prepared wastes, and some incidental items. The figure proposed broke down to a unit capital cost of $3350 per ton per day. If this figure were increased by $2650 per ton per day, or almost 80%, to offset inflation and to provide for items not covered in the initial proposal, the unit capital cost would be $6000 per ton per day, or 25% less than the outlay for the New York City incinerators.

Acknowledgements

The active interest and encouragement of Ralph E. Graham, Utilities Director and Eric Quartley, Public Works Director (retired) of the City of San Diego, aided greatly in this research. The assistance of members of the Neighborhood Youth Corps in carrying out the sanitary fill survey is acknowledged as is that of all others who participated in this project.

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